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Dr. Masa Noguchi is an Associate Professor in Environmental Design at the Faculty of Architecture, Building and Planning, University of Melbourne, specializing in “Environmental Experience Design (EXD),” decision-making analysis based on a mass customization framework that embraces machine learning and value engineering techniques for improvement of operational energy efficiency, affordability, and occupants’ wellbeing in the built environment. In parallel to EXD studies, he also initiated global movement on zero energy mass custom homes (ZEMCH) and vertical village/subdivision plug-in housing system research and development for future-proof city evolution.

In 2019 he was nominated Extraordinary Professor at the San Pablo Catholic University (UCSP) in Arequipa.

Conference
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Biography

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In parallel to teaching, he has worked as a designer in Colombia and Spain, having built some works. He has been a speaker and guest lecturer at several universities in Colombia and Europe. Dr. Sarmiento has publications in books and international magazines.

Conference
Towards a light construction

Theme
Sustainable Architecture
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Universidade de São Paulo
Brazil

Biography
Professor of Building Materials, Polytechnic School at the Universidade de São Paulo. Head of the CEMtec - National Institute for Advanced Cement-Based Technologies, and member of the board of the CICS USP - Sustainable Construction Innovation Center, University of São Paulo, ABC Modular – Brazilian Alliance for Modular Construction and hubIC, hub for innovation in Cement-Based Construction.

His research interests are on developing low-carbon & circular technologies for construction, particularly for the cement-value chain, and on industrial ecology applied to construction, specially developing simple and practical LCA-based metrics. Focusing on applied research, Prof. John’s work is mostly supported by industrial partners and government. He has published more than 100 papers on peer-review journals.

Conference
Simple metrics for a low-carbon, circular construction industry: The Brazilian experience

Theme
Building Energy, Performance & Technology
Biagio Giannetti
Universidade Paulista
Brazil

Biography
Dr. Biagio Giannetti is a Full Professor at UNIP, where he holds the positions of Professor of the Graduate Program in Production Engineering and Coordinator of the Research Laboratory (LaProMA). Since 2016 he has been a Visiting Professor at BNU (Beijing-China), under the National High-end Foreign Experts Recruitment Program. He also holds visiting professorships at UNISON (Sonora-Mexico) and UNIFI (Florence-Italy). His work includes books, articles and lectures, which deal with Production and Environment. In Scopus, his h-index is 30 and his i10-index in Google Scholar is 91. Dr. Gianetti is an Honorary Board Member of the Journal of Cleaner Production and is Associate Editor of the journal Frontiers in Energy Research. He is President of the International Society for the Advancement of Energy Research and Director of the Global Center of the Advances in Cleaner Production Network.

Conference
Towards more sustainable social housing projects. Recognizing the importance of using local resources

Theme
Environmental Sustainability and Policies
Rodrigo García
Universidad del Bío Bío
Chile

Biography
Rodrigo García has been a Visiting Scholar at U. Houston, USA; U. Strathclyde, UK; U. Kaiserslautern and Bauhaus-Weimar Universität, Germany; U. de Guadalajara, México; Georgia Tech, USA; Federal de Rio Grande do Sul, Brazil; U. Nacional del Litoral and U. Católica de Córdoba, Argentina; and Aalto U. of Finland. He is currently an Academic at the Department of Design and Theory of Architecture, and Director of the Doctorate in Architecture and Urbanism at the Universidad del Bío Bío, Concepción, Chile. Professor and Researcher in Digital Media for Architecture, Energy Simulation and Housing.

Conference
Switch over for sustainable and appropriate housing through 3D printing and solar energy

Theme
Sustainable Architecture
Biography

Dr. Cassia Ugaya is a Professor at the Universidade Tecnológica Federal do Paraná. She worked as a consultant for UNEP (currently UN Environment) and was co-founder of the Ibero American Life Cycle Network (LCA), the Brazilian Life Cycle Association and the Social LCA Alliance. She also contributes to the private sector, participating in the Brazilian LCA Business Network. She is Coordinator of the Technical Committee of Life Cycle Impact Assessment of the Brazilian LCA Program. Her h-index by Scopus is 15.

Currently she coordinates a research project financed by CNPq, a project with O Boticário Group, and another project with ecoinvent, financed by the European Commission and implemented by the Life Cycle Initiative of UN Environment. She coordinates the Working Group on Social Life Cycle Assessment (GTACV-S) since 2013. In 2020, she coordinated the project Plant and Share: For Nutrition and Food Security, one of the finalist projects of the NASA International Hackathon SpaceApps Challenge - Covid-19.

Conference

Life cycle sustainability assessment for a better future

Theme

Climate Change and Urban Resilience
Biography

Dr. Carlos Zeballos Velarde is a Peruvian Architect, Urban Planner and Researcher. He gained his PhD in Kyoto University, Japan, and did a Post PhD at the Research Institute for Humanity and Nature, Japan. He did internships in the United Kingdom and the USA, and he has served as a visiting professor in Russia, Mexico and Colombia.

As the former Dean of the Universidad Católica San Pablo’s Faculty of Engineering and Computing, he joined the ZEMCH Network and led various initiatives for its introduction in Peru.

As a Researcher, he is the recipient of the “Outstanding Paper and Design Award” at the World Congress of Architects in Seoul, Korea. He has also written multiple books and scholarly papers, and he was given an honorable mention in the 2022 National Biennale in Cusco for his “Environmental Atlas of Arequipa”.

He is now the Peruvian Architects Association’s National Director of Technological Affairs.

Conference
Urban resilience strategies

Theme
Climate Change and Urban Resilience
Carlos Formoso

Universidade Federal do Rio Grande do Sul
Brazil

Biography
Dr. Carlos Formoso is a full professor in Construction Management at the Federal University of Rio Grande do Sul (UFRGS), Brazil. He has a degree in Civil Engineering and M.Sc. from UFRGS, and a Ph.D. awarded by the University of Salford, UK. His main research interests are lean construction, mass customisation, production planning and control, safety management, social housing, and value management. Dr. Formoso has published more than 110 journal papers and around 40 books and book chapters. He has supervised 113 M.Sc. dissertations and 25 Ph.D. theses, and he is a member of the editorial boards of six international journals. Regarding international academic collaboration, he has been a Visiting Scholar in several universities and research institutions outside Brazil, including USA, Norway, UK, Chile, and Ecuador. For more than thirty years of academic career, he has developed several research projects in partnership with the industry, including public and private client organizations, contractors, real estate developers, and companies that deliver prefabricated systems.

Conference
Modular construction in Brazil: challenges and opportunities for implementing mass customisation

Theme
Sustainable Architecture
Biography

EED Fellow BD+C, LEED AP ID+C, Master in Corporate Real Estate (MCR), Fitwel Ambassador, Cradle to Cradle Accredited Assessor and GBC Casa e Condomínio Professional. Environmental Engineer and Master’s in chemical engineering from Universidade de São Paulo. Director of the Sustainability Unit at CTE, with more than 16 years of experience in Green Building. Her experience in implementing green building projects comprises different aspects such as energy efficiency, water use optimization, indoor environmental quality, sustainable materials analysis, and life cycle assessment to enhance the well-being of occupants, reduce environmental impacts and optimize operating costs. Associate Professor in the Mackenzie University, teaching at post-graduate level the class of sustainable materials and technologies. Chair on the GBCI Credentialing Steering Committee (CSC) and Member of Water Efficiency Technical Advisory Group - LEED Committee.

Conference

Carbon emissions in the construction sector & circular economy

Theme

Sustainable Architecture
Humanity has an enormous challenge in the days to come. Climate change and natural resources scarcity forces us to adopt new practices in every aspect of our lives. Crucial solutions appear, that is learn to develop energy zero houses and sustainable cities in order to address these problems that may affect human life in unthinkable ways.

Energy zero houses are very efficient in energy consumption. These houses are designed and built in ways that need very low external energy using available renewable energy sources such as solar and wind power. By reducing energy consumption, it is also reduced fossil fuels and climate change dependency. They also use sustainable construction materials, efficient design techniques and appropriate waste management systems. These practices help reduce greenhouse gas emissions, decrease air and water pollution, and conserve natural resources. In addition, they promote biodiversity by integrating green spaces and natural habitats into their urban planning.

In this context, the international scientific network Zero Energy Mass Custom Home ZEMCH, started in 2010 by the notable professor Masa Noguchi, has been actively participating in research and construction industry with the aim of addressing the problems that arise in the shaping of socially, economically, environmentally and humanly sustainable built environments in developed and developing countries.

The Universidad Católica San Pablo’s relationship with ZEMCH dates back to 2019 when, after a series of collaborations, Dr. Carlos Zeballos Velarde, then dean of the Faculty of Engineering and Computing Science, proposed Dr. Noguchi as a visiting scholar of our university. Later in Bangalore, India, Dr. Zeballos proposed the organization of the X ZEMCH conference to be held at the UCSP, being enthusiastically received by the ZEMCH scientific community. Likewise, the organization of this congress has involved the strong commitment of two academic departments through the professional schools of Architecture and Urbanism and Environmental Engineering, who have worked very hard for the development of this international conference.

We hope that this important meeting of students, scholars and businesspersons in Arequipa will bring new ideas and projects that may improve world citizen’s quality of life.
CHAPTER 1
Climate Change and Urban Resilience
Place building: Enhancing resilience in Hazard-Prone Public Areas. The case of Arequipa, Peru

Abstract: Like in many other cities in developing countries, a large part of Arequipa’s peri-urban territory is located in risk areas, particularly due the city’s proximity to Misti volcano and to seasonal ravines vulnerable to flooding. This situation results in social and physical fragmentation, leading to the detachment of local communities. For this reason, the authors propose the concept of “Place Building”, which is better adapted to the characteristics of urban contexts in cities of the Global South compared to the more ephemeral practice of “Placemaking”. Place Building is a tool that proposes the integration of fragmented communities near seasonal ravines through the implementation of evolutive, low-cost and easily implementable urban elements in public spaces. These elements act as catalysts, contributing to risk mitigation by improving the physical conditions of these vulnerable areas, thereby increasing their resilience to face hazardous events. The interventions are conceived from the outset to tackle substantial infrastructure challenges in public spaces, with development taking place in stages. This approach is especially helpful in a Latin American context, where the socio-political environment hinders the implementation of quality public spaces, particularly in peri-urban areas. To achieve this, a pilot area of intervention was selected, which articulates urban, environmental, social, and institutional aspects to enhance community resilience. Subsequently, an easy-to-build, identifiable, small-scale, replicable, and scalable prototype is proposed.

This prototype facilitates social exchanges and connections in public spaces, fostering the creation of organized social capital and laying the foundation for permanent projects that address the genuine needs of an organized community. Additionally, these interventions have the potential to improve the physical conditions of public spaces in marginalized communities and attract various stakeholders and investors.

Keywords
Place building; urban resilience; public space; participatory planning.

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1. Introduction

Architecture is a constantly evolving discipline, and over time, there have been various discussions about its practice. In recent years, several authors have emphasized the importance of embracing different notions and possibilities within the field, including a participatory approach [1, 2, 3]. Alternative practices of architecture entail approaches where architecture is not the sole protagonist but rather plays a role among other actors and agents. [2] Consequently, architectural practice can benefit from the interactions with other stakeholders and disciplines within the context where these relationships take place.

Over the past few decades, a series of collaborative processes that aim to actively involve citizens in the production of urban space and place have gained prominence. These participatory processes share the endeavor to break down hierarchies and have citizens as active instigators of change and reinvention in the city [4] [5]. Among these approaches, “Placemaking” has emerged as a people-centered process that seeks to improve citizen’s quality of life through the transformation of public spaces [6].

“Placemaking” not only pursues physical goals but also cultural and social objectives. The design and creation of great and vibrant public spaces are important aspects of the process that occurs during placemaking interventions. However, the building of social capital, the increase in communal engagement and participation, and the development of a shared community vision are some of the most valuable assets of this process. [7]. In summary, the physical transformation of a place is utilized as a tool to achieve profound social changes within a community.

Through the creation of accessible, inclusive, plural, and participatory public spaces, “Placemaking” can be used as a tool to expand the community’s capacity, foster the creations of common narratives, and cultivate a sense of identity and attachment [8]. However, it is important to acknowledge that the majority of literature on this subject primarily focuses on placemaking initiatives in the Global North, where participatory processes originated as means to disrupt large, entangled, complex, and top-down public systems with well-defined norms and operating procedures. In these processes, community participation has very defined characteristics and goals [6].

Nevertheless, it is crucial to recognize that while placemaking interventions in the Global North have been successful in achieving short-term transformations and a sense of community, they often lack long-term sustainability and fail to adequately address the complex and interconnected challenges faced by communities in the Global South. Participatory approaches in the Global South encounter distinct challenges shaped by the unique socio-political context of these regions. In addition to the limited presence and inefficiency of governments, cities in the Global South are predominantly composed of non-formal self-built settlements that have emerged through collective building processes. Therefore, these communities face numerous infrastructure challenges, especially the lack of quality public spaces. As a result, the characteristic ephemerality and temporality of placemaking [9, 10], which may be well-suited for the Global North, appear superficial in addressing the multitude of pressing needs, specially within vulnerable communities in the Global South.

For this reason, we propose the concept of “place building”, which incorporates the participatory and community-driven characteristics of “placemaking”, while adding a more permanent dimension since its conception. The interventions are planned and are part of a process that aims to construct a complete community facility in public spaces, although developed in stages. Place building processes have the potential to create social capital and a sense of identity, belonging, and commitment to the place built, and become a platform for the interaction of different stakeholders through the provision of time and space to listen, ask, understand, and learn from each other. Through these processes it is possible to address people’s needs and implement, if necessary, small-scale, simple, short term and low-cost interventions as a way to materialize the community vision in a short time and with few resources. This is especially helpful in a Latin American context where tight budgets, long bureaucratic processes, and complicated authorities hinder the renewal or creation of great public places. Likewise, when projects are carried out, many times the design proposal does not consider the collective memory of the place and the aspirations and daily needs of its inhabitants since, normally, they are not invited
to participate, or when they participate the processes are tedious and long, and several times do not come to be materialized.

The primary objective of Place-building interventions is to use architecture as a means of connection by creating spaces for citizens and different stakeholders’ encounters, both physical and social, that foster community participation and create social capital. Simultaneously, the implementation of what we call “small physical interventions” seeks to improve the physical conditions of deteriorated public spaces. By leveraging their characteristics of being easy to construct, small-scale, replicable, and scalable, Place-building interventions offer the advantage of shorter implementation timeframes compared to waiting for local governments to take action and invest in site improvements. Furthermore, these interventions lay the groundwork for permanent projects that cater to the real needs of an organized community. The design proposal for the permanent intervention can be driven by the organized community, a design team, and other stakeholders such as academia and local governments, who become engaged during the implementation of the Place-building interventions. The key distinction with placemaking lies in the fact that Place-building interventions are conceived from the outset to address a significant infrastructure challenge in public spaces, which is difficult for local governments to tackle with a single endeavor. Instead, by developing a network of different small physical interventions strategically located in the large area where the future infrastructure project will be developed, it becomes possible to achieve tangible physical improvements in a short time, foster social capital, attract various stakeholders, and collectively build the groundwork for a future permanent intervention. (Figure 1)

Figure 1. What is a Place building?
2. Materials and Methods

2.1 An introduction to the site

The city of Arequipa is the second-largest city in Peru and the capital of the province with the same name, housing a population of 1,080,635 inhabitants [11]. The city, sited at an altitude between 2,300 and 2,400 meters and flanked from north to east by a chain of high mountains, is crossed by the fertile valley of the Chili River, and it covers a territory furrowed by seasonal ravines known locally as "torrenteras". Its historic center is recognized as a UNESCO World Heritage Site, which is equivalent to 2% of the whole area of the city [12].

The city extends over a territory of 18,000 ha with a low net density of 101 inhabitants/ha [13]. This expansive growth has occurred, in many cases, in an unplanned and chaotic manner, carried out at first by migrants of low socioeconomic status and in the last two decades by land traffickers who have promoted a speculative expansion, in some cases in association with the authorities.

Many of these areas have grown on risk areas, particularly around the seasonal “torrenteras”, which during the rainy season can carry large amounts of mud and water flows and can cause floodings, as well as material and human losses [14] (Figure 2). Moreover, many of these streams are sources of contamination and social deterioration due to the abandonment of the local municipalities, since many of the streams are in turn district boundaries, which means that both neighboring municipalities disassociate themselves from their maintenance and development [15].

This analysis focuses on three of the districts located in the nearness of Misti volcano, which are Alto Selva Alegre, Miraflores, and Mariano Melgar. The main problem identified in these areas is its physical-spatial and social fragmentation. This rupture is due to the lack of connection between the different neighborhoods and urbanizations crossed by the ravines or that simply do not have urban continuity, and, furthermore, by the location of settlements in areas at risk of both flooding and
landsides. Likewise, it is caused by the rupture and social dissociation that occurs between the different settlements and by the indifference of the institutions and authorities in charge of their development or the overlapping of their powers.

This situation produces little articulation with the neighborhoods and with other surrounding areas, as well as the lack of fluid spatial neighborhood relationships. Regrettably, material and human losses also occur in the face of frequent disaster events in vulnerable settlements. Likewise, there is a lack of identity and social cohesion among the communities that inhabit these areas and, in particular, around the torrenteras that suffer abandonment and become contaminated and marginal spaces. (Figure 3)

2.2. Previous participatory diagnosis

In this sense, the “Costuras Urbanas” (Urban Linkages) project carried out a participatory diagnosis from 4 thematic axes: physical, environmental, socio-economic and institutional. This process includes 3 workshops with the population on each of the districts involved, involving children, adults and seniors as well as municipal technicians. A different kind of workshop was carried out with local experts in the fields of hydrology, risk disaster management, sociology and ecology, as well as a different workshop with an international expert from the UN-HABITAT [15]. This diagnosis favored a new and systemic conception of the periphery, where ravines function as integrating rather than dividing elements, taking on the qualities of “linear centralities” or “functional corridors” insofar as they can simultaneously house urban recreational and social integration activities and act as elements of ecosystem support and defense in case of flooding, fostering the resilience of vulnerable areas [16].

The idea that neighborhood centralities feed and interact with these transportation networks, which aim to transversely and longitudinally unite the city, was fundamental to this plan. A systemic approach is used to elaborate the proposed an urban planning scheme (Figure 4), it consists of:
a) System of centralities. It includes the main urban sector operations, which are characterized by permanent population flows during working hours and the development of significant public spaces.

b) Mobility system. It makes reference to the practical connection between the two urban regions that are divided by torrents. It consists of the following subsystems: communications, solid urban waste management, parking, transportation (integrated transportation systems, bus stops), and roadways (roads for vehicles, cycling paths, and pedestrian paths).

c) Public space management system. It means that social and environmental conditions must be improved in order to foster a sense of community. Green spaces and waterfronts are included as subsystems.

d) The landscape and image system. Formed by the urban design as well as the components of the physical, natural, and urban landscape (neighborhoods, nodes, highways, edges, and vistas) that are important in the collective memory.

This method identifies the projects that, from the perspective of urban acupuncture, would have a significant impact on the population and would result in a chain reaction effect that would, in the short, medium, and long terms, significantly lower the cost of carrying out an expensive complete urban renewal of this area [17].

Figure 4. Urban planning scheme proposed by the Costuras Urbanas project.
2.3. Proposed intervention

Taking this into account, we propose an intervention area located in the northwest sector of the ravine that divides the districts of Alto Selva Alegre and Miraflores. In this area we defined five interventions (Figure 5) in strategic locations that will connect the territory and promote the implementation of the Urban Renewal Project of this "torrentera". The role determined in the urban planning scheme, and the context's characteristics define the type and use of the proposed interventions.

Figure 5. Proposed interventions.
Given the characteristics and the challenges faced by the territories of the Global South, it is necessary to adopt an approach for adaptation and recovery that allows for efficient coverage of distinct demands. We argue that a replicable prototype would facilitate this, as it is a resource utilized by architectural movements aiming to address a range of unmet basic needs in vulnerable areas through rapidly executed, cost-effective architectural solutions that utilize local resources. [18].

The design of this prototype is based on four key design strategies: modularity, scalability, flexibility, and temporariness. Firstly, modularity entails that these interventions should consist of various interacting components that can be replicated, transformed, or replaced, as needed. Secondly, scalability enables them to evolve over time by adding more modules if necessary and to be easily replicated in other similar environments. Thirdly, flexibility allows these interventions to adapt to different situations, as the modules can be reorganized, deployed, transformed, or dismantled to accommodate the changing needs of their users. Finally, temporariness recognizes from their conception that these interventions have a predetermined duration, as they ideally pave the way for permanent interventions. They should involve low costs and facilitate ease of implementation, transformation, and possible dismantling, thereby enabling their components to be repurposed or integrated into other contexts.

3. Results

We propose the design of a prototype consisting of interchangeable components that can be easily combined, modified, or replaced to create various modules or small-scale physical interventions tailored to the needs and desires of the community. These interventions are intended to foster interactions and encourage active community participation during implementation, use, and potential reformation. Additionally, we plan to organize a series of meetings and events at the site, involving community residents, authorities, municipal technical teams, academic researchers, and other stakeholders interested in participating in the project. By incorporating elements such as seating, vegetation, and shade, the interventions aim to contribute to the short-term improvement of public spaces in the area. Furthermore, the interventions will undergo evaluation by the population, allowing for modifications, expansions, or replications, and may undergo formal and programmatic changes to align with the challenges and aspirations of the citizens who utilize them.

The prototype comprises two main components: a metallic frame and a base. The metallic frame is cube-shaped with dimensions of 3x3x3m and is painted in a vibrant color for visibility and easy identification in its surroundings. It consists of four supports, each composed of two U-shaped profiles measuring, attached to a rectangular pipe anchored to the concrete cube of the base. Two levels of rectangular pipes on the upper part provide rigidity to the entire structure. The base component addresses the need for a suitable flooring experience within the interventions, particularly in areas where the ground has not been treated. It proposes a buried base, delimited by a wide concrete curb, and filled with crushed stone rubble to create a non-sandy yet permeable soil for various activities (Figure 7).

These elements constitute the prototype, and additional components can be utilized. These components can be attached, changed, or removed according to user needs, resulting in various modules that can be adapted to different requirements and purposes. The components are categorized into three groups: enclosure, coverage, and complements (Figure 6)
By combining the prototypes with the components, a series of modules can be obtained, enabling the development of various activities to meet the needs and particularities of the different users in the selected intervention area. (Figure 7) In the initial phase of this project, we propose the implementation of three out of the five interventions proposed. These interventions will create public spaces for recreational, commercial, and social activities. (Figure 8)
4. Discussion

In the face of rapid urbanization and the challenges posed by climate change, the concept of Place-building has emerged as a potential alternative for fostering resilience while strengthening identity and a sense of community. Place-building involves transforming public spaces into vibrant, inclusive, and meaningful places that reflect the local culture and values by means of the creation of flexible, evolving and adaptive communal facilities.

Place-building emphasizes the importance of creating resilient environments that can withstand and adapt to various challenges, such as natural disasters, economic fluctuations, and social changes. Arequipa, located in a seismically active region, faces the constant threat of earthquakes. By integrating resilient design principles into the urban fabric, such as earthquake-resistant construction techniques, sustainable infrastructure, and disaster preparedness plans, Arequipa can enhance its ability to recover and thrive in the face of adversity.

Modular construction, also known as prefabrication or off-site construction, is a viable alternative for Place-building. Disaster-prone areas in Arequipa, with its unique urban challenges and need for sustainable development, can benefit from adopting modular construction practices. Six key aspects are proposed in this regard:
a. Speed and Efficiency: Modular construction involves the fabrication of building components off-site in a controlled factory environment. This approach allows for concurrent site preparation and off-site construction, resulting in reduced construction time. In Arequipa, where there is a need for rapid urban development to accommodate a growing population, modular construction can provide an efficient solution to meet housing and infrastructure demands.

b. Resilience to Seismic Activity: Modular construction involves the fabrication of building components off-site in a controlled factory environment. This approach allows for concurrent site preparation and off-site construction, resulting in reduced construction time. In Arequipa, where there is a need for rapid urban development to accommodate a growing population, modular construction can provide an efficient solution to meet housing and infrastructure demands.

c. Sustainability and Resource Efficiency: Modular construction often incorporates sustainable practices, such as the use of environmentally friendly materials, reduced waste generation, and energy-efficient design. These practices align with Arequipa's goals of sustainable development and resource conservation. By utilizing modular construction, the city can reduce its carbon footprint and promote a more sustainable urban environment.

d. Flexibility and Adaptability: Modular construction offers design flexibility and adaptability, allowing for customization and future expansion. This aspect is particularly relevant in Arequipa, where the preservation of historical buildings and integration with the existing urban fabric are crucial. Modular construction techniques can facilitate the construction of compatible structures that blend harmoniously with the city's cultural heritage.

e. Affordability and Accessibility: Modular construction has the potential to be cost-effective, especially when considering the shortened construction timeline and reduced labor requirements. This affordability can contribute to addressing the housing shortage and providing accessible housing options for residents in Arequipa. Additionally, modular construction can be employed in various types of buildings, including educational facilities, healthcare centers, and community spaces, making them more accessible to the population.

f. Integration: A group of modular constructions can form an interdistrict network of facilities by strategically placing them throughout different districts. Each modular construction can be tailored to correspond to specific neighborhood characteristics, incorporating design elements, materials, and amenities that reflect the unique identity of the neighborhood. This approach ensures that the facilities not only serve the overall needs of the city but also contribute to the preservation of neighborhood character and foster a sense of belonging among residents.
5. Conclusions

We propose the concept of Place-building as a more suitable approach for addressing the challenges faced by urban contexts in cities of the Global South, specifically focusing on vulnerable communities in Arequipa, Peru. Place-building is a tool that tries to encourage community engagement and social resilience in order to create long-lasting, practical, and evolving infrastructure. For this reason, structures that will offer efficiency, resilience, sustainability, adaptability, affordability, and integration to these marginal communities while also adapting to their unique needs and fostering a sense of identity are proposed for the risk areas in the outskirts of Arequipa. Our proposal discusses the limitations of traditional “Placemaking” practices in these regions, where the socio-political context and infrastructural challenges are different from those in the Global North.

Moreover, place-building encourages the involvement of local communities in shaping the urban environment. By engaging residents in the decision-making processes, encouraging participatory planning, and promoting cultural exchange, Arequipa can ensure that its development reflects the values and aspirations of its people. This sense of ownership and connection to the city’s evolution strengthens the collective identity and pride among the residents. Additionally, place-building places a strong emphasis on creating inclusive public spaces that facilitate social interaction and community engagement. Arequipa can invest in the development of areas that encourage residents to gather, connect, and engage in shared activities. These spaces can serve as platforms for cultural events, festivals, and community initiatives, fostering a sense of belonging and social cohesion.

Furthermore, the implementation of these modules that foster social, economic, and recreational activities will play a significant role in strengthening people’s connection to their public spaces. By providing comfortable and attractive platforms that accommodate different age groups, interests, and identities, these areas might strengthen the collective identity, foster emotional connections, and enhance the sense of belonging among its residents. Additionally, a board of trustees made up of three instances is suggested for the project’s financing: the consultants, made up of government and academic institutions, who are in charge of raising money and developing projects; the promoters, made up of the provincial municipality and district municipalities; and the supervisors, who include members of the organized public, such as churches and NGOs.

Finally, as the proposed place-building interventions are implemented and evolve over time, it becomes essential to conduct long-term impact assessments. These assessments should focus on understanding the social, economic, and environmental effects of these interventions on the communities they serve. They should also include the evaluation of community cohesion, social capital, economic opportunities, and overall quality of the resident’s life. Moreover, future research could delve deeper into refining and enhancing the participatory design processes employed in place-building interventions. Exploring innovative methods for engaging communities in the decision-making process and incorporating their visions, needs and aspirations can strengthen the sense of ownership and empowerment among residents. Investigating successful examples of participatory design in different cultural contexts can provide valuable guidelines for future projects. In this way, the concept of place-building can continue to evolve and adapt to meet the challenges and aspirations of urban communities in the Global South, promoting sustainable and resilient urban development for a diverse range of contexts.
The proposed interventions in the peri-urban areas of Arequipa are designed to foster social exchanges and connections in public spaces, laying the foundation for permanent projects that address genuine community needs. The results align with previous research that emphasizes the importance of community engagement and participatory approaches in urban design and planning. By involving citizens as active instigators of change and reinvention in the city, "Place-building" can create a sense of ownership and connection to public spaces, fostering a stronger collective identity and social cohesion. Furthermore, the use of modular construction techniques is suggested as an efficient and cost-effective approach to implement these interventions in Arequipa’s rapidly growing peri-urban areas. The adoption of modular construction can enhance the seismic resilience of public structures, promote sustainability and resource efficiency, and provide affordable and accessible public infrastructure options.

In conclusion, the concept of "Place Building" presented in this paper offers a promising approach to address the social and physical fragmentation in vulnerable communities near seasonal ravines in Arequipa. By integrating participatory planning, modular construction, and community engagement, "Place Building" has the potential to create resilient, inclusive, and sustainable urban environments that cater to the genuine needs of the local population.

References


11. INEI, «Censos Nacionales: XII de Población, VII de Vivienda y III de Comunidades Indígenas,»


Abstract: The "helada" (frost), is a climatic phenomenon that generates abnormally low temperatures in the high Andean zone of Peru. The settlers of these areas, mainly rural, are dramatically affected because their homes do not have sufficient thermal insulation. Various projects and programs have been financed to solve this problem without reaching a sustainable or commercially viable solution. The objective of the present investigation was to use a user-centered design approach in order to develop a product capable of satisfying requirements such as usability, cost, and effectiveness. At the same time, design and inventive methodologies such as the Theory of Inventive Problem Solving (TRIZ) were used. This tool allowed solving the technological contradiction of achieving a better level of thermal insulation at a low cost. As a result of the process, a new concept was obtained that we call "Cápsula de Vida", which, inspired by the concept of capsule hotels in Japan, consists of a small cabin capable of being introduced into a conventional room, which has a level sufficient thermal insulation (demonstrated by computer simulation), to promote a good rest, without impairing the possibility of developing key activities such as study, reading, and leisure. The system is modular, easy to assemble and transport.

Keywords: User-centered design; thermal insulation; High Andean zone; TRIZ; modular system.
Introduction

Due to their geographical location at high altitudes (above 3000 meters above sea level) and low cloud cover, the highland areas of Peru experience temperatures below 0°C during the winter months (May to September). This phenomenon, known by rural inhabitants as "helada" (frost), causes material damage, affects people's health, and has a negative impact on agricultural activities, thus affecting the economy of many families. [1] [2].

In many localities of the highland areas, houses are constructed using materials such as adobe and rammed earth for the walls, and roofs are made of corrugated sheets or fiber cement. Additionally, earthen floors and limited access to basic services like electricity, potable water, and sanitation are common. These conditions do not provide sufficient protection against low temperatures [3].

The low temperatures in the affected districts have severe consequences on health. There is an increase in respiratory diseases due to prolonged exposure to extreme weather conditions, particularly among vulnerable groups such as children under 12 years old and adults over 65 years old. The precarious housing conditions, with substandard materials and lack of thermal insulation, further exacerbate the vulnerability of these groups [4] [5].

In Peru, initiatives have been implemented to improve thermal comfort in rural highland dwellings. Some low-cost solutions, such as the use of the Trombe wall system (a method to capture solar radiation on one of the house walls), may have limited effectiveness in mountainous areas with few hours of direct sunlight [6]. Other alternatives have successfully improved thermal comfort conditions by implementing insulation enhancements [7]; furthermore, the utilization of high Andean natural grasses such as Ichu has been explored [8]. However, conventional insulation solutions in housing can pose a significant cost burden concerning the purchasing capacity of high Andean families.

The study aims to design a low-cost thermal comfort solution for low-income households affected by low temperatures. The last is achieved through a user-centered design approach and inventive problem-solving. Additionally, material quality, economic accessibility, ease of transportation, and environmentally friendly materials are considered.

Conceptual framework

User-centered design (UCD) focuses on identifying the needs and preferences of users when designing living spaces, taking into account daily activities, living conditions, and environmental limitations. This concept originated in creating interfaces and software systems for high usability and adaptability. The ergonomic variable is used to understand the precise needs of users. Furthermore, it is aligned with ISO 9241-11:2018 to enhance user experience and productivity in developed systems [9]. On the other hand, the application of UCD focuses on developing sustainable environments, considering, among others, the energy perspective [10].

On the other hand, architectural designs, similar to product development processes, require systematic methods and decision-making throughout all stages, from conceptual design to prototyping. From this perspective, the TRIZ method offers a tool to address complex design problems by utilizing 39 design criteria and 40 Inventive Principles, which foster creative thinking and the resolution of technical contradictions [11].

Furthermore, computational simulation software tools have been applied for the development of construction solutions, enabling the calculation and simulation of various environmental parameters [12]. By simulating different material variants, improvements in design can be achieved, such as reducing energy consumption and achieving efficiencies of up to 30% [13]. Thermal simulation can be optimized under different climatic conditions to meet temperature and humidity parameters related to comfort [14].
## Materials and Methods

### Selection of the locality

Two fundamental stages were conducted, macro-location and micro-location, to consider extreme climatic conditions and accessibility to the study area. In the macro-location, two main aspects were taken into account: the annual occurrence of frost-related adverse effects on the population in Peru [15], [16] [17], and the geographical proximity to the research team. In the micro-location assessment, three key aspects were evaluated: climatic data, including recording minimum and maximum temperatures, evaluation of transportation accessibility to ensure quick and efficient access for project logistics; and guarantee of the sustainability of the proposed solution. On the other hand, a review of previous work related to the topic was carried on, aiming to better understand the challenges and needs faced by the population under study.

### Identification of design criteria

The UCD approach was employed to gather detailed information on the needs and preferences of the users. This approach involved three fundamental aspects: defining the profile of the individuals, conducting a semi-structured questionnaire covering six key dimensions (socio-economic, basic services, housing, thermal comfort, habits and customs, and general conditions). At the same time, an interview guide was created, aimed at local authorities to understand the importance of similar projects and assess the health situation of the residents. Additionally, a detailed observation guide was developed to collect specific information on the characteristics of the houses. These methods allowed for a comprehensive understanding of the users’ needs and contexts, thereby contributing to a design tailored to their requirements.

### Identification of technological contradictions

In order to conduct the design process, the TRIZ methodology was employed. This technique involves the identification of problems and goals, followed by the definition of a conceptual design. Subsequently, the TRIZ matrix was used to identify relevant contradictions. Then, with the design team’s support, various solution ideas were generated.

### Testing of the conceptual design from thermal simulation contradictions

The study utilized the Design Builder software, integrated with the validated EnergyPlus calculation engine, to conduct precise energy simulations for a proposed rural housing solution in high Andean regions. The simulation used for modeling the solution, considering ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards for energy simulations [18]. On the other hand, meteorological data (www.meteonorm.com) was used to simulate and predict the annual climatic conditions to which the solution was exposed. For this purpose, latitude and longitude search parameters were used [13]. The selection of commercially available materials was carried out to improve energy efficiency based on climatic conditions. The thermal performance of these materials was evaluated to achieve more significant energy savings [19].
Results

Selection of the locality

During the process, three potential locations in the Department of Arequipa were evaluated, specifically Andahua, San Antonio de Chuca (Imata), and Sibayo. It was determined that Imata provided the most comprehensive and up-to-date climatological information, as well as experiencing the most extreme temperatures, reaching below -15 degrees Celsius. Additionally, Imata is an accessible location, with a distance of 132 km from the city of Arequipa. Furthermore, socio-economic studies have been conducted in this area. [20] and even specialized in thermal comfort and the use of renewable energies [21] [22] [23]. These conditions allow us to approach the study with higher-quality information.

Information for identification of design criteria

In order to identify the design criteria, four sources of information were used: profile of the inhabitants, survey information, observation and interviews.

Profile of the inhabitants

Not all residents of this locality live there due their economic reliance on livestock farming. Livestock farming occurs in the nearby estates, which are approximately 20- to 30-minute away.

Regarding the impact of frost on the lives of the residents, it has been observed that the community’s health is precarious, as they tend to react to health issues rather than adopting preventive measures.

Survey information

The following Table 1 presents a summary of the main findings obtained from the survey application:

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Summary of Information Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Socio-economic</td>
<td>Generally, the households are occupied by at least two individuals whose main occupation is commerce or homemaker, with an average income of less than 500 soles.</td>
</tr>
<tr>
<td>Basic services</td>
<td>In general, there is access to basic services, although, in the case of water, it can vary in source and quality.</td>
</tr>
<tr>
<td>living place</td>
<td>They lack food preservation and heating appliances. Furthermore, they do not have fixed or mobile internet. Multiple families usually share the rooms, meaning that there may be more than one bed per room.</td>
</tr>
<tr>
<td>Thermal comfort</td>
<td>The lowest temperature occurs at 03:00 hrs, directly affecting the health and sleep of the inhabitants.</td>
</tr>
<tr>
<td>Habits and customs</td>
<td>The residents’ nocturnal activities are limited, mainly involving listening to the radio or watching television. Engaging in activities such as reading or similar tasks is challenging due to the exposure to low temperatures.</td>
</tr>
<tr>
<td>General conditions</td>
<td>The habitability of the area is limited, not only due to the temperatures but also the water quality. Despite having a low tariff, water is a source of illnesses.</td>
</tr>
</tbody>
</table>
Observation information

The houses predominantly feature dirt floors without specialized coating. The roofs are made of corrugated iron. Some have polystyrene or raffia ceilings to maintain temperature. Flat doors and wooden windows that do not allow much light are common. Most houses have 2 rooms, often without separations for family members. One room serves as a bedroom, and another as a kitchen. House height exceeding 3 meters prevents rainwater stagnation.

Interview Information

Through interviews with local authorities (Parish Priest, Mayor, Chief Medical Officer of the health center, and Tambos Builder), knowledge was obtained about the existence of government initiatives aimed at reducing the impact of low temperatures, focusing primarily on the provision of warm clothing for the residents. On the other hand, there is a reference to past projects that aim to improve insulation and thermal comfort. For example, in the parish premises, a demonstration house incorporates thermal insulation technology. However, its implementation proved costly due to underfloor heating with copper pipes carrying hot water beneath the floor.

Identification of design criteria

Based on the profile of inhabitants, the survey information, observation and interviews, design criteria were identified: It is established that the housing should have good enough insulation in order to maintain a suitable average temperature during the hours of the day with the lowest temperature. Additionally, the housing should have the capacity to accommodate at least two adult individuals, providing sufficient space for a bed, a wardrobe, and a table. Furthermore, it is required that the housing be adaptable and equipped with the necessary electrical connections. The solution should be low-cost, easily transportable, and capable of being assembled practically and straightforwardly. Among the different design criteria, two were considered key for this analysis: the need of good insulation and the low cost.

Application of TRIZ methodology

The requirement for effective insulation and cost-effectiveness of the solution gives rise to a technical contradiction. The goal is to minimize energy loss caused by inadequate insulation, while also considering that a larger insulated area or volume entails higher costs. This technical contradiction can be described in terms of the following parameters:

- (TRIZ parameter 22) Energy waste.
- (TRIZ parameter 6) Area of an object without movement.

According to the TRIZ matrix, this technical contradiction suggests exploring the following inventive principles:

- (TRIZ inventive principle 07) Nesting. Inserting objects within others to utilize empty space and optimize the size and transportation of the system.
- (TRIZ inventive principle 17) Changing the physical state of a substance to solve problems or improve systems.
- (TRIZ inventive principle 30) Using thin films or membranes to enhance the properties and functionalities of objects or systems.
According to the results, it was decided to adopt the nesting principle. As illustrated in the figure, this principle involves placing one object inside another, similar to the nesting dolls known as matryoshka dolls [24]. This principle leads the team to create a small housing module (resembling a Japanese-style micro-room) that offers high comfort and is placed within the traditional dwelling. This approach allows for the necessary insulation at a lower cost than insulating the entire house while adhering to the design criteria.

**Figure 1.** Nesting criteria and conceptual solution based on the Matryoshka example

**Heating system simulation**

The simulation utilized properties of construction materials from the Design-Build and CIBSE (Chartered Institution of Building Services Engineer) libraries [18]. Metabolic thermal gains and occupancy schedules have been considered when establishing a ventilation airflow rate of 14 L/s [25]. Mechanical ventilation was utilized to ensure indoor air quality and meet the established standards. This approach was quantified in the thermal balance of the system.

The most extreme environmental conditions recorded during the coldest weeks of the year were considered. For the annual simulation, meteorological files extracted from Meteonorm were used (https://meteonorm.com), which include solar radiation [26].

**Figure 2.** Temperature Profile and Thermal Balance
Figure 2 illustrates the temperature profile achieved by the solution. The blue line represents the outdoor temperature, the gray line represents the temperature inside the conventional house, and the red line represents the temperature inside the "Cápsula de vida". The figure demonstrates that during the coldest hours (between 9:00 pm and 7:00 am), the temperature remains close to 10°C, even when the outside temperature drops below -5°C. During these cold hours, there is a temperature difference of approximately 5°C between the conventional house and the "Cápsula de vida". Similarly, the thermal balance shows that during the coldest hours, the person’s occupancy (between 7:00 pm and 7:00 am) proves to be significant in raising the system's temperature. Additionally, the figure reveals that the main heat losses occur through the windows and insulation defects.

Finally, using the concept of "cápsula de vida" requires a significantly lower amount of energy to achieve a comfortable temperature of 18°C [27] [28].

Discussion

Observations of housing conditions in Imata highlighted the need for improved housing infrastructure to enhance thermal insulation and comfort. The design criteria were subsequently identified to focus on providing good insulation to maintain suitable average temperatures during the coldest hours, accommodating at least two adult individuals comfortably, and ensuring adaptability, necessary electrical connections, low-cost, easy transportability, and straightforward assembly.

To address the technical contradiction of effective insulation and cost-effectiveness, the TRIZ methodology was applied, leading to the adoption of the nesting principle. Inspired by matryoshka dolls, this approach involved creating a small housing module resembling a Japanese-style micro-room, placed within existing traditional dwellings. This concept allowed for effective insulation at a lower cost, aligning with the identified design criteria.

The heating system simulation validated the effectiveness of the proposed "cápsula de vida" housing module, maintaining a temperature difference of 15°C from the outside and 5°C compared to a standard home during the coldest hours. While there was a significant improvement, achieving ideal comfort temperatures may necessitate additional heating. Nonetheless, heating costs would be considerably lower compared to the baseline conditions.

The simulation emphasized the impact of occupant presence on raising indoor temperatures and identified opportunities for enhancing the home’s design, particularly in addressing windows and insulation issues.
Conclusions

The application of User-Centered Design (UCD) in rural housing enables the development of solutions tailored to the needs of communities facing extreme conditions, resource scarcity, and limited services. This tool involves using efficient construction techniques and comfort systems to create resilient and comfortable homes, thereby improving the quality of life for inhabitants. Furthermore, UCD considers local residents' preferences and cultural traditions, ensuring that architectural solutions align with their values and lifestyles.

The TRIZ technique generated alternative solution options to meet the design criteria. These solutions were achieved through inventive problem-solving based on the logic of technical contradiction.

The concept of "Cápsula de vida" meets design parameters. It is a high-comfort concept that provides good insulation quality in a comparatively small area, thus reducing insulation costs. An ergonomic design can offer comfort to rest and the performance of intellectual and leisure activities, which can significantly benefit the inhabitants of high-altitude communities.

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Conflicts of Interest: The authors declare no conflict of interest.

References


17. C. Vilca Umiña, Estudio de un sistema de Control Adaptativo para Contrarrestar las Heladas en los Cultivos utilizando Riego por Aspersión en la Región Altiplánica de Puno, Puno: Universidad Nacional del Altiplano, 2014.


Flood risk management in the ravine of San Lázaro in the city of Arequipa - Perú

Abstract: The city of Arequipa, the second most important in Perú, faces many extreme challenges, such as high-intensity but short-in-duration rainfalls which causes floods and the swelling of the Chili River (mud and landslides). This situation exacerbates people’s condition who live on the margins of the ravines and gullies, because of little or no territorial planning from public institutions. (1) The local news evidence negligence every year in the human and infrastructural loss. The frequency of these events has increased with the time and that is the reason why rainfall thresholds have been created with their identification together with a 42-year register (1981 – 2022). (2) For the hydrological model, the authors used the highest 24-hour precipitation data from the SENAMHI’s stations (National Service of Meteorology and Hydrology of Peru) to obtain the liquid hydrograph for different return periods. Soil mechanics studies were also carried out to determine the rheological parameters of the non-Newtonian flow and then calibrate through historical events in a hydraulic model. (3) Finally, cartographic maps were prepared to evaluate the vulnerability and high-risk areas of flooding in the San Lázaro ravine.

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Keywords
Extreme events; Rainfall thresholds;
Hyper-concentrated flows;
Flood; Vulnerable; Risk; Perú.
1. Introduction

Perú is highly vulnerable to climate change, a situation that is exacerbated with inequality, poverty, and population growth of the country [1].

According to INEI (National Institute of Statistics and IT), Arequipa had a population of more than 1 million 316 thousand people [2]. Due to heavy rainfall occurring every year, this study focuses on describing the events that occur during the rainy season in what is called maximum rainfall. The obtained thresholds provide an external rainfall climatic index with a pragmatic and internationally recognized method that, instead of deducing the density probability function, measures the extreme events thresholds through the empiric probability function. For this purpose, geotechnical, hydrological, and hydraulic studies were carried out in the ravine San Lazaro.

Every year floods and overflow in areas around the basins and gullies that flow and join at Chili River in Arequipa cause the collapse of sewers, drains, and fields in the lower parts of Misti volcano. This occurs because of short duration and high-density rainfall takes place in the city. In the last 20 years, extreme storms are becoming more frequent because of climate change which causes more critical flows towards existing gullies [3].

2. Materials and Methods

The Quilca – Chili basin is on the western side of the Andes and is part of the Pacific Ocean watershed. The Quilca river flows through Arequipa’s province on the southern-west part of Peru between 15° 37’ 50” latitude south and 16° 47’ 10” and 70° 49’ 15” and 72° 26’ 35” latitude west. The city of Arequipa (see Figure 1) is strongly affected by floods of irregular frequency due to the overflow of the gullies located on both sides of Chili River. According to the diagnostic shown by the Hydric-Resource Management Plan of the Quilca-Chili Basin [4], the city contains the highest risk area for mudslides, primarily because of the indiscriminate growth of the town. This growth is caused by a lack of planning, a deficient sewer system and the invasion of the natural river channels.

![Figure 1. Location of the city of Arequipa and the gullies around Misti volcano.](image-url)
2.1 Maximum Rainfall Thresholds

Thresholds are indicators related to rainfall, water level or flow hazard. A common criterion for rainfall differentiation is setting the precipitation thresholds as climatic indexes (see Table 1). This procedure followed the one described by Alfaro [5], which is used as technical rule in SENAHMI. The information used to calculate thresholds is the daily rainfall of a long-register climatological station. It is also mentioned that these indexes are justified because there is more information available on accumulated rainfall (daily rainfall) in 24 hours than rainfall intensity.

<table>
<thead>
<tr>
<th>Rainfall thresholds</th>
<th>Differentiation of extreme rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR/day &gt; 99p</td>
<td>Extremely rainy</td>
</tr>
<tr>
<td>95p &lt; RR/day ≤ 99p</td>
<td>Very rainy</td>
</tr>
<tr>
<td>90p &lt; RR/day ≤ 95p</td>
<td>Rainy</td>
</tr>
<tr>
<td>75p &lt; RR/day ≤ 90p</td>
<td>Moderately rainy</td>
</tr>
</tbody>
</table>

* RR/day is the quantity accumulated of rainfall in 24 hours.
* 99p, 95p, 90p, 75p, are the percentiles shown in %.

2.2 Basic studies

2.2.1. Geology

According to the Ministry of the Environment [MINAM] (2018) [6], Arequipa has lava streams on the northeast part of the city which come from Misti and Chachani volcanoes (NpQ-ba-s) and are cut by the canyon of Chili River. The city and its surroundings are deposits of alluvial fans (Qp-al) because of the mud flows and the volcanic deposits in the southern area.

2.2.2. Topography

-The topographic survey of the main torrents was carried out using a DJI Phantom 4 RTK drone. The topographic map was illustrated with contour lines each meter, georeferenced from a benchmark provided by the Geophysical Institute of Peru (IGN) in the World Geodetic System WGS84/UTM Zone 19S.

2.2.3. Hydrology

Thouret et al. [7] gave the mapping and cartography as supporting sources for danger and risk due to sudden floods and lahars (volcanic mudflows) in San Lazaro and Huarangal gorges based on the morphology of the channels. However, a rainfall-runoff analysis is required to determine the maximum channels through a hydrological sample based on data collected (La Pampilla Station). The boundaries of the channels were set based on good practices developed in Qgis by Der Kwats and Menke [8] (see Figure 2). They determine the physiographic and geomorphologic features in each ravine of the study based on the digital elevation model (DEM) ALOS – PALSAR at a resolution of 12.5 m.
The fluid hydrograph was obtained using data of 24-hour maximum rainfall from La Pampilla stations with a 42-year register (1981 - 2022). A frequency analysis was carried out on the data using the non-parametric goodness-of-fit Smirnov - Kolmogorov test with a level of significance of $\alpha=0.05$, for different probability distribution functions and to know which would adjust better to the maximum data series an extreme value theory was considered to differentiate the extreme rainfall events as mentioned by Endara [9], extreme value generalized distribution. Then, to determine the hydrograph, the HEC - HMS hydrologic sample was used with the methodology of Soil Conservation Service (SCS, 1986) to know the effective rain with the curve number (SCS, 1972) and the transformation rainfall runoff method through the unit hydrograph. For this study, the storm distribution SCS – Type II, which estimates hydrograph inflow for 24-hour rainfall and distribution Type II due to work with high Andean channels, was used. The parameters for the HEC – HMS sample are the ones shown in Table 2.

### Table 2. Parameters of the ravine of the study

<table>
<thead>
<tr>
<th>Micro Channel</th>
<th>Surface Area Channel (Km²)</th>
<th>Average Gradient (%)</th>
<th>Curve Number (CN)</th>
<th>Concentration Time (Tc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Lázaro</td>
<td>17.0</td>
<td>42.8</td>
<td>84.4</td>
<td>52.0</td>
</tr>
</tbody>
</table>

Concentration time in minutes.
The gullies located on the left margin and merge together at Chili River show gradients of the main basin at 18% (see Figure 3).

![Graph of San Lazaro Ravine](image)

**Figure 3.** Longitudinal profile of ravine San Lazaro until the confluence at Chili River.

<table>
<thead>
<tr>
<th>Micro Channel</th>
<th>Flow (m³/s) for different return periods (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TR=5</td>
</tr>
<tr>
<td>San Lázaro</td>
<td>15.9</td>
</tr>
</tbody>
</table>

* TR: Return period.

### 2.2.4. Soil Mechanics

Alpine erosion takes place through soil pits in critical points by the entrance of the city of Arequipa (see Figure 2), so that the geotechnical features through lab trials could be calculated. Predominant presence of extended granulometry (rocks, boulders, gravel, sands, and fine material).

### 2.2.5. Hyperconcentrated flows

In the hydrograph (Figure 6), the liquids represent rainfall (precipitation), the solids represent rocks, gravel, sand, and fine material that can be transported by alluvial flows. To know the solids, either volume or weight, O'Brien et al. [10], determined the volumetric concentration of the solid material with rheological parameters estimated with empiric values given by Rickenman [11], from 1600 kg/m³ to 2000 kg/m³ for mud flows and from 1900 kg/m³ to 2300 kg/m³ for debris flow. In this way, to determine these solid volumetric concentrations, formulas proposed by Takahashi [12] were used (equation 1) assuming a stable flow in movement [13].
Cv = (γb*S)/(γS-γb)(tgθ-S)

Where: γb: Specific mud weight (1.0 - 1.6 ton/m³); γS: Solid material specific weight (2.6 ton/m³); S: Average gradient of the flow and gorge and internal friction angle θ of the solid material (30° - 35°).

3. Results

Table 4. Meteorological stations

<table>
<thead>
<tr>
<th>Meteorological Stations</th>
<th>Longitude (°)</th>
<th>Latitude (°)</th>
<th>Altitude (m.a.s.l.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>La Pampilla Station</td>
<td>-71.534</td>
<td>-16.413</td>
<td>2326</td>
</tr>
</tbody>
</table>

Table 5. Historical Record

<table>
<thead>
<tr>
<th>Meteorological Stations</th>
<th>Time Frame</th>
<th>N° of years</th>
<th>Data number</th>
</tr>
</thead>
<tbody>
<tr>
<td>La Pampilla Station</td>
<td>1981 - 2022</td>
<td>42</td>
<td>15,340</td>
</tr>
</tbody>
</table>

In La Pampilla station, accumulated rainfall data from 962 rainy days was organized from lowest to highest (RR>0.1mm). The percentiles were calculated for 931 rainy days, except for the highest value recorded (124.5 mm) due to extraordinary rainfall, Caca et al. [14] and extreme value statistics. There were 281 missing pieces of information in the time series. statistics. There were 281 missing pieces of information in the time series.

Table 6. Maximum Rainfall thresholds in La Pampilla station

<table>
<thead>
<tr>
<th>Rainfall thresholds</th>
<th>Extreme rainfall differentiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR/day &gt; 99p</td>
<td>RR &gt; 25.4 mm</td>
</tr>
<tr>
<td>95p &lt; RR/day ≤ 99p</td>
<td>14.5 mm &lt; RR ≤ 25.4 mm</td>
</tr>
<tr>
<td>90p &lt; RR/day ≤ 95p</td>
<td>9.5 mm &lt; RR ≤ 14.5 mm</td>
</tr>
<tr>
<td>75p &lt; RR/day ≤ 90p</td>
<td>4.5 mm &lt; RR ≤ 9.5 mm</td>
</tr>
</tbody>
</table>
3.1 Flood drill

Hydrologic analysis is made to define risk maps in case of floods. This would determine the magnitude of a low-probability (100 years) storm discharge and a hydraulic sample to estimate the flow depth, according to Mazar et al. [15]. In Peru, ANA (National Water Authority) is a public institution attached to Ministerio de Agricultura y Riego (Ministry of Agriculture and Irrigation), which is responsible for establishing rules and set procedures for the integrated and sustainable management of hydric resources so that primary use of water, water protection, free transit, fishing, etc, can be guaranteed. To set a higher limit of the riverbank, a marginal strip, where is highlighted that in areas surrounding natural or artificial channels of water sources that are near human settlements, there is a return period of 100 years according to Use and Management of Marginal Strips [16].

3.2 Calibration of the sample

The calibration was made considering maximum rainfall records (1981-2022), which caused historical events in Arequipa: 1995, 1997, 2001, 2002, 2012, 2015, 2016 and 2020, with an adverse meteorological phenomenon, statistically seen as less probable. Martelli [17], summarized nine events that damaged the city of Arequipa in repeated scenarios of 5 to 10 years. Despite this, the calibration of the hydraulic sample was made for a TR=5-year return period, using the rainfall threshold analysis as the extreme rainfall indicator through historical events that have taken place in Arequipa, affecting buildings placed near the channels. The ravine of study is characterized by being dry almost all year, given that they are only activated during high-intensity rainfall or extreme hydrologic events, such as the ones in 2020. The water level under different infrastructures in the coated channels is a common feature (see Figure 5).

Figure 4. La Pampilla Station (1981 - 2022) – Daily maximum rainfall data.

A. San Lázaro ravine (Juan de la Torre Ave). B. Undermining. C. Strong rainfall and Mud flow entering the bus station
The figure 6 shows the mud flow hydrograph for San Lazaro ravine, made based on the liquid or water flow hydrograph.

**Figure 6.** Liquid and mud flow Hydrograph of San Lazaro ravine, TR=100 years.

Field evaluation and the main hydraulic parameters through numerical simulations (Table 8), evidence of historical events, vulnerability points and risk areas against maximum avenues.

**Table 7. Maximum flow for different return periods (TR)**

<table>
<thead>
<tr>
<th>Ravine</th>
<th>Máximo flow (m³/s)</th>
<th>Máximo flow (m³/s)</th>
<th>Flow (m³/s) for different return periods (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>TR=5</td>
</tr>
<tr>
<td>San Lázaro</td>
<td>Water flow</td>
<td>-</td>
<td>15.9</td>
</tr>
<tr>
<td></td>
<td>Mud flow</td>
<td>1.14</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>Debris flow</td>
<td>2.44</td>
<td>38.7</td>
</tr>
</tbody>
</table>

*Cd: Thickening factor.

**Table 8. Evaluation of results for disaster risk management**

<table>
<thead>
<tr>
<th>Gullies of the study</th>
<th>Risk area/Infrastructure</th>
<th>Frequency of events</th>
<th>Return period</th>
<th>Maximum water depth</th>
<th>Maximum flow speed</th>
<th>Total flooded area</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Lázaro gully (8.5 Km)</td>
<td>Cahuide bridge</td>
<td>High (every 3 to 5 years)</td>
<td>100</td>
<td>4.8</td>
<td>6.3</td>
<td>23.4</td>
</tr>
<tr>
<td></td>
<td>Juan de la Torre Ave.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. Discussion

The Gullies are straight and steep channels, dominated by a unidimensional flow (1D) Bricker et al. [18] using this information infrastructure like bridges and pontoons are present in the city of Arequipa through transversal areas and considering coefficients of expansion, contraction and the conditions of the surroundings or limits for an ID sample. In this way, knowing the height of the flow in the lower part of the infrastructure chart allows us to model using a bidimensional flow approach (2D) with HEC – RAS. This approach solves the bidimensional differential Saint – Venant differential equation and applies the finite-volume method instead. For that application, the cell size of 5x5 meters and a computational interval of 3 seconds.
5. Conclusions

The hydrological modelling analysis was made for the ravine of the study: San Lazaro. The analysis was made applying the model HEC-HMS and the hydraulic modelling of the gullies with the HEC-RAS model for a 100-year return period. The calibration of the sample was carried out considering the records of historical events between 1981 - 2022 (42 years), characterizing 24-hour maximum rainfall (15,340 pieces of information) with an "extremely rainy" threshold (99 percentile) which happens approximately every five years in the city of Arequipa.

The behavior of water flowing through analyzed channels show critical depth and velocity, which cause undermining and erosion besides overflow and flood areas due to extreme rainfall, which is becoming more frequent. To answer this high risk in the city of Arequipa, we proposed energy dissipation systems such as staggered falls at bridges and retaining walls.

Acknowledgments Catholic University of Santa Maria for its financing in which this applied research project was carried out.

References

1. The Intergovernmental Panel on Climate Change [IPCC]. (2022). Working group II contribution to the sixth assessment report of the intergovernmental panel on Climate Change Impacts, Adaptation and Vulnerability. Fact sheet – Central and South America.


Ecosystem services of blue-green infrastructure (BGI) for climate change adaptation and mitigation in an arid region

Abstract: Urban rivers are blue-green infrastructures of great importance due to their multiple ecosystem services which strengthen habitat connectivity and biodiversity. Cities in arid regions are vulnerable to climate change and face several problems: Inadequate response to floods; scarce availability of water resources; river pollution; urban landscape transformation; and urban heat island effect. Arequipa, an arid city in south Peru, has an urban section along the Chili River which flow allows the development of energy and agricultural activities; however, there is a gradual loss of the corridor due to environmental phenomena and anthropic alterations. The aim is to evaluate the ecosystem services offered by the urban river, which will allow a holistic understanding of its potential as a measure for climate change adaptation and mitigation. The main ecosystem services were determined through an evaluation (surveys) by national and international experts. Afterwards, based on a bibliographic review, the ecosystem services determined were associated with their capacity for adaptation or mitigation of climate change in Arequipa. The results of the surveys showed that the most important ecosystem service provided by an urban river is environmental education, which is considered fundamental for participatory governance involving multiple stakeholders. The main ecosystem service provided by the Chili River is the freshwater provision. Most of the ecosystem services contribute to climate change adaptation; however, air quality regulation and air purification through carbon capture and storage were identified as mitigation mechanisms. It is concluded that the preservation of the urban river and its ecosystem services contribute to increasing the overall level of resilience of the city. Management of this ecosystem, based on the recognition of the ecosystem services that urban rivers provide, will be essential considering the value of this type of blue-green infrastructure as a strategy for adaptation and mitigation of climate change.

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Keywords
Ecosystem services; blue-green infrastructure; climate change adaptation and mitigation
1. Introduction

The blue-green infrastructure (BGI) consists of an interconnected landscape network which includes water bodies (blue) and natural, semi natural and artificial open green spaces. These can be located around, inside and between urban areas in multiple scales [1,2]. BGI is the most important biophysical and ecological connection of cities with surrounding ecosystems. However, this is usually very disturbed due to diverse urban impacts [3,4], therefore, it must be strategically planned and designed in order to balance the human-nature relationship [2,5].

Urban rivers are ecological corridors that represent a very valuable BGI type because they maintain habitat connectivity, protect and promote biodiversity, and reduce landscape fragmentation caused by urbanization [6]. They are key elements to face climate change due to their multifunctional impact in ecosystem services (ES) provided by them [1,3,5,7-13,15]. However, the ES providing this kind of BGI, are being seriously degraded due to anthropogenic modifications and fast urbanization processes [5,12,17,18] that deteriorate the integrity of urban rivers and their riparian areas [3]; followed by other social, political and economic factors [17] which affect people’s quality of life [4]. Thus, it is understood that this BGI must be valued and cared for in a sustainable way in order to prevail the subsistence of people and the environment [3], moreover, it helps develop an ecological identity sense in people [18].

Nowadays, BGI is more studied and applied in developed countries with some limitations. This is probably because of interdisciplinary design requirements, lack of professional knowledge and uncertainties with respect to its financial and ecological [5]. In developing countries, BGI is little explored and because of that, it is still an increasing topic of debate and a challenge [2] due to these countries face pressing problems because of their fast population growth, the inability to address climatic and environmental risks, inefficient management and policies, limited economic resources [1] and growing urbanization without formal actions that respond to an integral urban [19]. BGI must not only be considered as an element to be integrated in an urban environment, but as a structured element in non-consolidated urban areas [20]. In addition to this, it is necessary to understand the ES dynamics related to the food, hydric and energetic systems in a city in order to achieve adequate planning, management and governance [14], overcoming environmental injustice [11]. Therefore, one of the first issues to solve is the identification of the first ES provided by the BGI which requires a deep examination to promote sustainability of the urban environment. [3,5,14]. Because of this, it is important to consider that the BGI urban management must be connected to the socioeconomic dynamics of each region with its corresponding cultural, economic and political characteristics [14].

Studies carried out about the ES provided by the BGI are based on systematic reviews of literature [6,7,14,21] which have generally been done through searching of keywords [1,12]. In addition to this, a socio environmental diagnosis can be carried out [17] as well as, perception and/or social preference [4]; surveys and discussion boards [11,17,21]; interviews and expert inputs [11,17]; indicator analysis through quality criteria [22]; ecological footprint analysis [23]; impact analysis in the ES, linked to anthropogenic activities and their effects in human well-being [5] and economic valuation analysis–ESV [16]. The geospatial study is also important for the ES multicriteria analysis [16]. The remote sensing application, geoprocessing and the use of SIG allows it to manage a wide range of information for BGI planning and management [3,24]. In addition to this, the ES and the impact in their variations can be valued and quantified by using software such as, InVEST [25] and DESSIN [5]. Future research should continue exploring empirical experiences for BGI [5] and the ecosystem benefits that they provide, especially those related to the climatic change [1] for being considered as one of the most promising actions for adapting cities to the fast human and environmental changes [7]. This must be recognized in the urban planning process, especially in the formulation of regional development strategies [7,14] which allow overcoming barriers that are imposed to apply the BGI, emphasizing on the identification of financing and collaboration mechanisms among different local sectors [1].

In this way, Arequipa City in southern Peru, was chosen as a study case. Arequipa is part of the hydrographic basin of Chili River, bounded by the Andes Mountain range to the northeast, and to the southeast by the Atacama Desert, at 2329 m.s.n.m high. It is located between the coast and mountain regions, surrounded by active volcanoes [26]. Its climate is temperate continental type. It is considered
as an arid region due to low rainfall whose annual variation is in a range of 27.20 mm., and important daytime thermal oscillations. The city presents rainy summers, concentrating rainfall between January and February, but the rest of the year, it is characterized by a deficient average relative humidity of 34% [27]. Arequipa is the second largest city of Peru, in population and economic terms, and hence, it is one of the most relevant urban zones nationwide [28].

This city is growing under a mono-centric development model which together with an explosive territorial expansion has become an indiscriminate urban growth, increasing the necessity of urban transportation, as well as, the pollution rates, urban fragmentation and disarticulation with existing natural ecosystems [28]. These problems generate urgent challenges that must be faced, such as; inadequate response capacity facing heavy rain events, the limited availability of hydric resources, the pressure on the ecological corridor of the Chili River, the pollution of its water and the potential heat island effect in the historic center due to a deficit of green areas and loss of intra-urban agricultural areas [26]. In that sense, Arequipa has the urban section of Chili River which crosses the city acting as an axis in its territorial configuration; along its route, it adjoins urban, historical and agricultural areas. Its basin provides urban and rural waters which allows the development of agricultural and energetic activities [29]; and represents an emblematic place for citizens [30]. In spite of its environmental, landscape, cultural and recreational values, there is a gradual loss of the ecological corridor of the river due to environmental phenomena and anthropic alterations 361 that have diminished the ES given to the city. Currently, studies aimed to decontaminate its waters and to understand their physicochemical, hydrobiological and biodiversity aspects have been carried out [32-34]; however, research focused on ES that allows to understand in a holistic manner the potential of urban rivers as a measure to deal with climate change has not been developed.

As a first step in addressing these issues, the objective of this study is to identify the ES offered by the Chili River in its urban section in order to evaluate which ones are the most valued and to differentiate those that are related to adaptation and to diminish climate change. Recognizing the interrelations among urban systems and the BGI through their multiple ES, represents an important opportunity to optimize the community development and their cities in order to address the problems related to the search for sustainable development. This study will serve as a starting point for a future comprehensive plan for the renaturation of the river; and as a tool for territorial planning, policy formulation and management of this type of BGI in arid regions with consolidated urban environments and in the consolidation process.

2. Materials and Methods

The investigation is based on a 5-phase scheme detailed as follows: The urban section of the Chili River was defined according to Durán, Pons and Serrano [21,35] from the application of a criterion of standardized distances around the riverbeds, adjusted to the existing urban legislation for the case study the Plan de Desarrollo Metropolitano de Arequipa [28]. Subsequently, two types of urban sections were differentiated; first, the “intra-urban” ones that have urban uses on both banks, and second, the “peri-urban” ones that have urban uses on a single band. It is considered that the fluvial section must be urban whenever there is material urban coverage in a 100 meter range measured from the Banks of the river and in the entire perimeter surrounding it. Isolated urban infrastructures were discriminated against, so urban developments whose surfaces are greater than 20 ha are taken into account and contribute to the consolidation and functionality of the urban frame.
Under the ES framework developed by the Millennium Ecosystem Assessment [36], a literature review was done to identify the ES to be evaluated in the surveys in order to select the largest possible number of ES characteristics of the mentioned rivers by different authors. This review was carried out using a search string with keywords such as; “ecosystem services”, “blue-green infrastructure” and “urban rivers” where 14 documents among papers, books and reports were considered [19,21,37,38]. Because green infrastructure is not a relatively new topic, the methodology of this paper excluded studies that only considered green infrastructure ES without a measure of blue infrastructure.

Two Likert scale surveys were developed [39] in order to evaluate the perception corresponding to 32 international experts with respect to the importance of the urban rivers ES in a 3-month period. Consequently, from these results, a second perception evaluation to 20 local experts regarding water management related to the Chili River in a 3-month period was carried out too, so that the most important ES can be selected based on the results obtained.

The scale was built from 1 to 5 where 1 is Not Important and 5 is Very Important. First, the international survey was carried out, applying an Analysis of Variance (ANOVA) and Tukey’s pairwise comparison [40] in the Minitab 19 software for the ES importance ratings according to the Likert scale and thus, to be able to filter the ES having significantly greater or equal to 4 average media [24] in order for these to be evaluated in the local survey applying the same procedure.

Finally, based on a literature review [41] the ES provided by the BGI were associated according to their capacity for adaptation or mitigation to climate change in the City of Arequipa.

3. Results

3.1 Definition of the urban section of the Chili River, Arequipa Peru

The study area is defined by the urban and peri-urban area around Chili River (Fig. 1) which is made up of the Riverside area and residential sector with presence of green areas along the riverside corridor. Three sub-sections were identified as part of the urban section of Chili River. The first section is delimited from the Santuario Virgen de Chapi – Charcani to the Chilina Bridge, considering the northern peri-urban sub-section. The second section, from the same point until reaching the San Isidro Bridge, is considered the intra-urban sub-section, as it presents urban uses on both banks of the river. The third section is delimited to the south to the Congata Bridge where
3.2 Identification of ES-ecosystem services

Based on the literature review [19,21,37,38] a list of 36 ES hydric resources associated to BGI: Urban rivers was obtained (Table 1).

Table 1. Literature review of ecosystem services associated to BGI.

<table>
<thead>
<tr>
<th>Identified ecosystem service per type</th>
<th>Supply</th>
<th>Regulation</th>
<th>Cultural</th>
<th>Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B: Erosion control and soil maintenance</td>
<td></td>
<td></td>
<td>1C: Scenic beauty</td>
<td>1D: Functional maintenance of ecosystems</td>
</tr>
<tr>
<td>2B: Nutrient storage</td>
<td></td>
<td></td>
<td>2C: Eco-tourism, recreation</td>
<td></td>
</tr>
<tr>
<td>3B: Control of pests and diseases</td>
<td></td>
<td></td>
<td>3C: Education</td>
<td></td>
</tr>
<tr>
<td>4B: Drought control</td>
<td></td>
<td></td>
<td>4C: Mental and physical health</td>
<td></td>
</tr>
<tr>
<td>5B: Regulation of rainfall regimes and Albedo Effect</td>
<td></td>
<td></td>
<td>5C: Legacy or cultural heritage</td>
<td></td>
</tr>
<tr>
<td>6B: Productivity maintenance of aquatic ecosystems.</td>
<td></td>
<td></td>
<td>6C: Traditional knowledge</td>
<td></td>
</tr>
<tr>
<td>7B: Air purification through capture and storage of atmosphere carbon.</td>
<td></td>
<td></td>
<td>7C: Spiritual and intellectual interactions</td>
<td></td>
</tr>
<tr>
<td>8B: Water quality</td>
<td></td>
<td></td>
<td>8C: Research</td>
<td></td>
</tr>
<tr>
<td>9B: Water flow regulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10B: Risk reduction due to flooding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11B: Thermal comfort, reduced energy use</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12B: Local climate regulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13B: Air quality regulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14B: Fire protection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15B: Maintain populations and habitats</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16B: Pollination</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17B: Flood and landslide control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. Map of the urban basin of Chili River and its defined sub-sections.
3.3 Results of the International Evaluation of the ES importance of urban rivers

As a result of applying the ANOVA (Analysis of Variance), it is determined that out of the 36 ES evaluated, only 23 have a media greater than or equal to 4. The service with the lowest value included was ES air purification, with an average of 3.969. These ES evaluated are considered to be the most important ones, that’s why they are taken into account for the local survey. The pooled standard deviation was used to construct confident intervals which shows why the lengths are similar in the graph of Figure 2, the 13 ES whose media are notably less than 4 are also observed.

![Figure 2. Graph of media and intervals for the results of the International assessment of 36 ES](image)

3.4 Result of the local evaluation of ES importance.

In the case of local evaluation, the same evaluation as the international methodology was followed. In Figure 3, we can observe that the ES with a media less than 4 are: spiritual and individual interactions, thermal comfort, reduction of energy use and regulation of rainfall regimes and the albedo effect.

![Figure 3. Graph of media and intervals for the local results of the Local Evaluation of 23 ES](image)
### 3.5 Differentiation of ecosystem services and climate change

#### Table 2. ES of the urban section of Chili River associated with adaptation and mitigation mechanisms to the climatic change.

<table>
<thead>
<tr>
<th>Type</th>
<th>Adaptation</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply</td>
<td>1A</td>
<td></td>
</tr>
<tr>
<td>Regulation</td>
<td>6B, 8B, 9B, 10B, 12B, 15B, 17B</td>
<td>7B, 13B</td>
</tr>
<tr>
<td>Support</td>
<td>1D, 4D, 5D, 6D.</td>
<td></td>
</tr>
</tbody>
</table>

The resulting ES of the evaluations, for the urban section of Chili River, were differentiated according to their capacity for adaptation or mitigation facing the climatic change (Table 2).

It is established that for both, local and international experts, many of the ES related to the climatic change adaptation that can be supplied by the urban section of the river are important. Only in the case of cultural ES, it is established that they do not have a direct relation to adaptation or mitigation measures to climatic change.

### 4. Discussion

Through this research, the most important ES provided by an urban river (Chili) have been identified as a type of BGI presented in an arid region prone to extreme hydrometeorological phenomena, such as: droughts and flash floods, as a results of short-term rains, and due to the effects of climatic change. These events have increased globally [42] so the study case is relevant for cities that have similar conditions as established in the Sustainable Development Goal 13: Climate Action.

The results of the international evaluation indicate that the most important ES is environmental education [43]. This demonstrates that most participant experts are professors and researchers, and for them environmental education is their first option because it constructs the people’s adaptive capacity in socio-ecological systems as urban rivers, increasing their resilience for the acquired knowledge [44,18]. Environmental education supports society to understand the respect for the environment being considered as fundamental in a participative governance that involves multiple actors and a sustainable management of resources [44].

The results of the local evaluation indicate that the most important ES is fresh water supply which is considered one of the main ES provided by the BGI [44]. This finding responds to the human need for subsistence. Historically, the first human settlements were strategically located near a river because this ensured the supply of indispensable consumption resources to live [45]. This is the case of the City of Arequipa and Chili River where the watershed to which it belongs supplies water to numerous city districts, satisfying urban use and economic activities such as agriculture and cattle raising [29]. It is important to consider that determining the most important ES for a region, depends on the location of the population along the river, the same as their respective cultural, economic, and political characteristics [14]; as well as the idiosyncrasy of communities and their traditions [46].

By examining the ES provided by the urban river as adaptation strategies and mitigation facing the climatic change, it is observed that most of them contribute to adaptation. The ES about freshwater
supply is represented as a strategy to adapt to climatic change because this factor has a meaningful impact on hydric resources [37]. It is predicted that the demand for water in the urban area of Arequipa will increase by 80%, therefore, better water management in the hydrographic basins or watersheds could guarantee its availability for use in economic activities, such as; agriculture and its supply to urban areas [47]. Due to Arequipa’s desertic climate and the evaluations of meteorological disaster risks carried out [26], it has been determined that droughts are frequent in this area [48], therefore, it is extremely important the sustainable management of the hydric resource.

An adequate BGI management and its ES of regulation can be a long-term functional and profitable way to reduce risks and adapt to the climatic change [49]. The restoration of these ES in urban areas would have a significant impact in the regulation of water floods, the mitigation of floods and other disaster risk events. In addition to this, it is recognized that the BGI plays a very important role in local climate regulation by helping to mitigate the heat island effect, improve shading and air flow and contribute to regulating the temperature of ecosystems [49,41]. These services are essential to adapt to the climatic change and strengthen resilience of ecosystems facing their impact on them. Although the regulation ES are mostly related to adaptation mechanisms in front of the climatic change, two services have been identified: Air quality regulation and air purification through carbon capture and storage as mitigation mechanisms. An effective ES management can reduce emissions, increase the carbon capture and maintain or increase carbon sinkholes [50]. Also, long and short-term mitigation and adaptation actions will be determinant for risks provoked by climatic change because mitigation can reduce the necessary adaptation scale [51]. Due to the important role of ES and their management fighting the climatic change and associated risks [1,14] the need for a greater commitment from the authorities in ES management and their integration in territorial planning and regional planning of climatic change is highlighted [7,14], taking urgent measures and adopting solid strategies that address these challenges [7] in order to guarantee resilience in arid regions as Arequipa.

With respect to the formation of identity and cultural heritage, cultural ES play a fundamental role [15,18]; though they are not directly related as mitigation or adaptation strategies, some of them are valuable and very important for a particular community [1], because of this, they must be valued and cared for. In this sense, ancestral knowledge transmitted by different indigenous communities are especially relevant to adapt to the climatic change [52]. This knowledge acquires meaningful importance in rural areas with arid and semi-arid climate where adaptation is achieved through planning of this knowledge [53].

It is important to consider that the City of Arequipa presents an indiscriminate urban growth similar to most Latin American cities due to the lack of effective governability and adequate planning [48] and it also has consolidated urban areas and others in consolidation processes. Faced with this problem, the application of the BGI as a socio ecological system would help structure and organize the city growth, as well as, providing a sustainable and resilient solution faced with the climatic change challenges.

Future research should complement the ES study provided by the BGI by applying digital tools, remote sensing and the use of SIG for a holistic understanding of the topic. In addition to this, management and financing mechanisms should be explored as strategic alliances between public and private actors that facilitate the protection, restoration and/or application of these types of ecosystems in cities.
Author Contributions: Conceptualization, Carla Irurí, Andrea Chanove and Berly Cárdenas-Pillco; methodology, Karla Vilca and Lorenzo Carrasco; software, Lorenzo Carrasco; validation, Karla Vilca and Lorenzo Carrasco; investigation, Carla Irurí, Andrea Chanove, Berly Cárdenas-Pillco, Karla Vilca and Lorenzo Carrasco; writing—original draft preparation, Karla Vilca and Lorenzo Carrasco; writing—review and editing, Carla Irurí, Andrea Chanove and Berly Cárdenas-Pillco; funding acquisition, Carla Irurí and Andrea Chanove.

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References


44. Krasny, M. E.; Lundholm, C.; Plummer, R. Environmental education, resilience, and learning:


47. Flörke, M.; Schneider, C.; McDonald, R. I. Water competition between cities and agriculture driven by climate change and urban growth. Nature Sustainability 2018, 1, pp. 51–58. https://doi.org/10.1038/s41893-017-0006-8.


Impacts of urban sprawl on the ecological connectivity of landscapes in the Chili River, Arequipa – Peru

Abstract: Changes in land use and road construction in areas of natural landscape character, such as the riparian landscapes that form the water backbone of the city, have generated a series of ecological conflicts at different scales and overexploitation of ecosystem services. It is for that reason that this research analyzed ecological connectivity and Morphological Spatial Patterns (MSP) with the moving window method and landscape metrics to understand the impacts of urban expansion from the spatial autocorrelation using Geographic Information Systems (GIS) between the built-up area, crops and pastures. The results over the last 6 years show the increase of mostly irregularly shaped built-up areas by 6.16% over cropland and grassland. This change is significant because both the loss of vegetation cover and the form of the architecture are potential elements responsible for the fragmentation of the riparian ecosystem, weakening it and causing a lack of ecological connectivity. The most evident fragmentation occurred in the north and south of the study area due to the saturation and variety of land uses. Finally, a process of ecological rehabilitation modified over time is detected in the middle zone that avoids edge changes in the landscape. This could represent the feasibility of ecosystem rehabilitation as an alternative in the search for optimization for a management that achieves a balance between urban expansion and ecological conservation.

Keywords: urban sprawl; ecological connectivity; river; riparian landscape; morphological spatial patterns.

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1. Introduction

Natural habitats face increasing stress as a result of rapid urbanization [1] and are thus at risk of fragmentation. Like the urban watershed of the Chili River in southern Peru, where the main cause of the lack of ecological connectivity is due to urbanization processes resulting from anthropogenic changes that transform landscape models and over-exploitation of ecosystem services [2], implanting roads, producing a fragmented ecosystem conforming patches of different sizes and separated from one another, changing the continuity between them, which is important for the conservation of species.

MSPs analysis was used to evaluate the ecological impacts of urban sprawl [3,4] which, together with the connectivity approach [5], allow the evaluation of landscape heterogeneity [6], and even allow its application in building ecological networks and green infrastructure [7].

2. Materials and Methods

To demonstrate the influence of urban expansion on the Chili River, MEPs were analyzed. The research objectives were to: (a) Assess land use transfers along the Chili River; (b) To assess whether spatial changes in land use are correlated during the urbanization process, based on the Patton Index and Compactness Index; (c) To analyze the impact of urban sprawl on landscape connectivity in the Chili River from the Vogelmann Index.

The study area was delimited in accordance with Municipal Order (MO) 739-2012 (755-2012) Delimitation of the Chili River Urban Basin (Municipalidad Provincial de Arequipa, 2017). To precisely analyze spatial and temporal changes in land use and landscape connectivity; land use data from 2017 to 2021 have been downloaded from the Global Land Use/Land Cover (LULC) map derived from ESA’s Sentinel-2 imaging with a resolution of 10m. whose data were mainly classified into 11 cover types: water, trees, flooded vegetation, crops, built-up areas, bare soil, snow, clouds, and grasslands [8].

3. Results

3.1. Transfers in land use along the Chili River.

Over the past 6 years, there have been noticeable changes in land use in the Chile River Valley, the built-up area increased from 5.60 km² in 2017 to 6.79 km² in 2021, which is 6.16% whereas the acreage of cropland decreased from 7.64 km² in 2017 to 7.03 km² in 2021 which is 3.15%. As well, pasture was reduced from 5.98 km² in 2017 to 5.20 km² in 2021, representing 4.05%. Compared with all three land use patterns, others have not changed much.

To track the transfer of land use, a comparison was made between 2017 and 2021 based on the relationships between cropped land use, built-up area, and pasture. In Zone 1, the change in the use of pasture per built area was highlighted, as shown in Figure 1, whereas in zones 2, 3 and 4 the land use change took place in the crops per built area, in addition to modifying with various forms the ecological connectivity. The conclusion is that, in most areas, cultivated areas were the principal source of construction land.
3.2. Patton index

To estimate the change resulting from urban expansion, the Patton Form Index was applied. The results obtained are presented in terms of the number of fragments between the years 2017 to 2021 where round and round oval-type patches were obtained in the crops. However, with respect to the size of the fragments, those of greater dimensions were irregular or amorphous as shown in Figure 2. There is a large, affected area in most of the study area that has mostly a severe ecosystem that has become very fragmented and weakened, because it has had a greater edge effect.
Moreover, in 2017, irregular fragments were found in the southern middle of the study area, which varied over the years, from an amorphous oval to an oblong rectangular oval to eventually become rectangular. Although the rectangular and irregular forms were the weakest compared to the other forms, these variations may indicate that the ecosystem has been rehabilitated in this part of the area.

To understand this behavior in form patterns, the 2021 Patton Form Index was superimposed on a 2022 land use survey. Figure 3 shows that in Sector 1, the form of Patton was irregular because of the saturation of the variety of land uses, while in Sector 2 the form of Patton showed a rectangular shape which was not so affected, possibly because the number of diverse land uses is minimal compared to Sector 1. Another important factor could be the shape of the construction that molded or changed the edge effects on the landscape.

Figure 3. Overlay analysis between current land uses vs. Patton Form Index using the moving window method with a 300 x 300m grid.

3.3. Compaction Index

Figure 4 shows a comparison of the Compaction Index for 2017, 2019 and 2021, which showed that the oblong oval fragments combined with the rectangular fragments could contain a non-fragile ecosystem by 2019. However, by the year 2021 the rectangular fragment already showed fragility results. In addition, these variations in a few years could demonstrate the probability of change in fragility, because of interventions that derive from ecological rehabilitation.
3.4. Vogelmann Spatial Continuity Index

From the Compaction Index and the Patton Index, the values obtained from the Vogelmann Spatial Continuity Index formula were obtained, where values greater than 4 were obtained, thus showing the spatial discontinuity in the ecosystem of the Chili River Basin. In conclusion, urbanization had a great impact on the landscape pattern, directly affecting the connectivity of natural habitats.

4. Discussion

The results show that the intensification of urbanization in the Chili River Valley led to a high degree of fragmentation, agreeing with Montesinos Tubée et al., [9] especially in the north and south due to the variety and saturation of land uses causing the loss in ecological connectivity, while in the middle zone has been varying its fragility according to the years, perhaps due to the low concentration of activities or form of construction.

Through the correlation analysis between the MSPs it was determined that in the intermediate zone is reflected housing areas without much rectangular shape, rather organic, which could even determine the way of building without fragmenting the ecosystem or weakening it even more, when the shapes are rectangular and become irregular or amorphous the ecosystem is weakened causing a lack of connectivity, as also indicated in the research of Mitchell et al., [5] and Z. Wang et al., [2].

Land tenure changes play an important role in the way land is managed which is evident in the northern zone where an urbanization is consolidating and appropriating a protected “Parque Ecológico las Rocas”, which could be shown in disagreement with other research such as that of Kjelland et al., [10], in which it is indicated that having that change of land they become intact. However, this does not happen in the study area due to governmental informality; on the contrary, activities intensify from the moment a road is consolidated due to factors such as demographic pressures, changes in markets, technology, policies, among others.
5. Conclusions

The results show that in the last 6 years the changes are significant and that in a short time it is possible to go from a state of non-fragility to one of fragility due to the processes of anthropogenic activities derived from urbanization, roads or agriculture that affect the ecological connectivity and lack of protection of the species.

In the north of the study area there is evidence of an exponential change of land use from pasture to housing, which not only affects the ecological connectivity but also affects an area called “Parque Ecológico Las Rocosas”, which contains attractive and unique landscapes that even within the M.O. 739-2012 (755-2012) contemplates it as a protected area.

In the center of the study area, there is a change of variation between the forms that the Patton Index shows, this area is close to the “Parque Industrial”, which contains in its left margin unconsolidated areas, but without many varieties of uses. This could mean a weaker and more fragmented sector, unlike the northern sector, which could also be due to the illegal appropriation of land, which endangers the land used for pasture or cultivation, offering more opportunities for urban expansion.

The heterogeneity of the assessment of landscape fragmentation not only reveals the impact of the environment and anthropogenic activities on the pattern, but also leads to the ways of building within a space immersed in nature, it has been seen that straighter and more irregular shapes produce more fragmentation than curved and organic shapes which could mean the importance of form in building without breaking with the imbalance of nature and thus the fragility of an ecosystem. Therefore, these results can provide political guidance for decision making and thus ensure sustainability in the city and the conservation of nature, where it is necessary to rethink the city without compromising ecological conservation in which a balance can be reached from development strategies based on scientific evaluation, to reasonably occupy surrounding areas that do not compromise biodiversity.
References


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Exploring the thermal resilience of a housing prototype in the United Arab Emirates

Abstract: With the accelerated extreme weather events caused by climate change, buildings are facing a challenge of remaining habitable during these events. These extreme weather events can lead to power outages and structural damages to the built environment. Therefore, the building research community has been investigating how to enhance the resilience of buildings to face these extreme events. Thermal resilience is one of the building design aspects that is still overlooked. Thermal resilience refers to the ability of a building to remain thermally habitable during an extreme weather event. To this end, this paper aims to explore the thermal resilience of a two-storey affordable housing prototype in the Sheikh Zayed Housing Program (SZHP) in the United Arab Emirates (UAE) using building performance simulation (BPS). A base case energy model was created for the housing prototype using the EnergyPlus whole building simulation engine. The base case energy model of the housing prototype was simulated considering the absence of an active cooling system. Then the indoor operative temperature ranges were examined and the thermal autonomy (TA) of the housing prototype was calculated. Ten alternatives of the base case energy model were created using passive energy efficiency measures (EEMs) to windows, walls, and roof. The finding of this study demonstrated that the tested prototype requires further attention during early design stages to be thermally resilient. Additionally, the results indicated that implementing single passive EEM has limited benefits in improving thermal resilience. Recommendations were made for further investigation including testing combinations of passive EEMs.

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Keywords
Thermal resilience; Climate change; Thermal autonomy; Affordable housing
1. Introduction

With the accelerated pace of climate change and its related extreme weather events such as heatwaves, flooding, and storms, an urgent need to reexamine the way we design, construct and operate our buildings is emerging [1][2]. As people spend more than 90% of their time indoors [3], designing, constructing, and operating buildings that can withstand such events and at the same time satisfy comfort, health, and well-being needs of occupants is a priority[4]. Extreme weather events such as heat waves and storms can lead to power outages that leaves buildings’ environmental systems (i.e., HVAC) inoperable [5]. This would result in overheated indoors, discomfort, and even fatalities in vulnerable populations such as the newborn and the elderly [4]. Despite the significance of the influence of the climate change caused by weather events, building codes are yet to adopt measures that would ensure the resilience of buildings to such events [1], [6].

Despite the absence of an agreed upon definition of resilience in buildings, resilience in general terms is defined by the UN General Assembly Resolution 71/276 as “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management”[7], [8]. In light of this definition, resilience in buildings can be simply defined as the ability of a building to remain habitable during and after extreme natural events such as heatwaves, flooding, earthquake, etc. Thermal resilience, as one of the aspects of building resilience, is defined by Siu et al. as “the building’s ability to remain at and/or to recover to a habitable state after a disruptive event (such as power outage) where mechanical equipment is not providing heating, cooling or ventilation”[1]. It is also defined by Kesik and O’Brien as “how the building-as-a-system, including its constituent materials, components and assemblies, manages various forms of thermal stress”[9], [10]. In addition to its importance to make buildings habitable during extreme weather events, thermal resilience in buildings can assist in the reduction of energy use and carbon emissions as it is primarily achievable through passive energy efficiency measures [10], [11]. Therefore, there has been a growing body of researchers who are investigating thermal resilience of buildings. For example, Sheng et. al. [12] conducted a holistic modeling and analysis study to evaluate the thermal resilience of a seniors’ residence (i.e., elders care home) during a heatwave that lasted six (6) days. The study concluded that the existing conditions of the building does not offer an acceptable level of thermal resilience and recommended the application of passive measures such as natural ventilation and increasing thermal insulation to improve the residence’s thermal resilience. Ji et. al. [13] conducted a study to quantify the zone-level improvement of thermal resilience after implementing a cooling retrofit. The study proposed a new metric to quantify thermal resilience called Thermal Resilience Index (TRI). The study also concluded that achieving resilience at building level and zone level requires implementing multiple design strategies [13].

Thermal resilience in buildings can be quantified using metrics/indicators such as Thermal Autonomy (TA) and Passive Habitability (PH). TA is a measure of the fraction of time a building can remain habitable without HVAC in operation while PH is a measure of the duration in which a building remains habitable following an extended power outage during an extreme weather event [10]. These metrics/indicators (i.e., TA & PH) are typically calculated based on results obtained from building performance simulation (BPS) which has seen an increased use within the architecture, engineering, and construction (AEC) industry over the last few decades.

Over the last few years, the United Arab Emirates (UAE) was no exception to the global phenomenon of climate change and its durable consequences. For example, in the past few years, hospitals reported increased numbers of patients that are admitted due to heat-related illnesses in the UAE [14]. Buildings in the UAE are relying heavily on HVAC to make the indoors habitable [15]. Additionally, it is projected that the average temperature in the UAE will rise 2.8°C by 2050 as a result of climate change [15]. In light of these unprecedented climate conditions, heavy reliance on HVAC poses a challenge for building designers. The designers’ focus has to become not only on providing
comfortable indoors during regular operations but also during extreme weather events and even when the HVAC is inoperable due to a power outage as increased demand on electricity for cooling purposes could lead to power outages [8], [10]. Therefore, there is a critical need to evaluate the thermal resilience of new and existing buildings and implement resilience enhancing measures early in building design and retrofit processes.

To this end, this paper aims to (1) evaluate the thermal resilience of a housing prototype from the Sheikh Zayed Housing Program (SZHP) in the Emirate of Abu Dhabi (AD), UAE, (2) assess the impact of implementing passive energy efficiency measures (EEMs) on the housing prototype resilience, and (3) provide high-level recommendations for improving thermal resilience in housing in the UAE.

The paper is structured to first present the methods and materials including information about the housing prototype, the energy model and the simulation-based investigation approach and tools. Then, the results of the simulation-based investigation are presented. The results are discussed thereafter outlining the major insights and conclusions.

2. Materials and Methods

In this section we present our approach to achieve the research objectives. The investigation approach is presented first then the base case energy model is described in detail.

2.1. Investigation approach

To evaluate the thermal resilience of the housing prototype and investigate design/upgrade strategies that would improve the thermal resilience, the following steps were followed:

a) A base case energy model was created based on published and unpublished information about Sheikh Zayed Housing Program.

b) The energy model heating, ventilation, and air conditioning (HVAC) system was turned off to mimic a power outage during which the building resilience will be assessed.

c) The simulation was performed using the weather data of Abu Dhabi (the capital city of the UAE). The simulation was run for a full year with a time-step of 1 hour for a total of 8760 time-steps.

d) The hourly indoor operative air temperatures of the model spaces were examined and the hours within the operative temperature range (15 – 30°C) that makes the building habitable were counted. The habitable temperature range was determined based on a study conducted by Ozkan et. al. [16]. Operative temperature is the temperature that people feel and it is a function of air temperature, the mean radiant temperature and surface temperature in space [17].

e) The thermal autonomy of the building was calculated using the following equation:

\[
\text{Thermal autonomy (TA)} = \frac{\text{number of hours within acceptable temperature range}}{\text{total number of hours in the year (8760h)}} \tag{1}
\]
f) Ten alternative energy models of the base case were created by applying passive EEMs to the base case one at a time. The ten alternative energy models were simulated. Table 1 below shows the EEMs applied to the base case.

Table 1. Passive EEMs applied to the base case model to improve TA

<table>
<thead>
<tr>
<th>Case</th>
<th>Wall U-value (W/m²·K)</th>
<th>Roof U-value (W/m²·K)</th>
<th>Window U-value (W/m²·K)</th>
<th>SCHG*</th>
<th>Infiltration Rate (ACH**)</th>
<th>Exterior Shading (side fins and overhang) depth (m)</th>
</tr>
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<td>Base case</td>
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<td>2.2</td>
<td>0.268</td>
<td>0.35</td>
<td>NA</td>
</tr>
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<tr>
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<td>2.2</td>
<td>0.268</td>
<td>0.35</td>
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<td>2.2</td>
<td>0.268</td>
<td>0.35</td>
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</tr>
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<td>1.19</td>
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<td>0.50</td>
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<tr>
<td>case_10</td>
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<td>0.14</td>
<td>2.2</td>
<td>0.3</td>
<td>0.35</td>
<td>1.00</td>
</tr>
</tbody>
</table>

*Window solar heat gain coefficient  
** Air changes per hour

g) The thermal autonomy (TA) was calculated for each alternative model and compared to the thermal autonomy of the base case.

h) Recommendations are made for improving resilience in SZHP single family housing prototype.

2.2. Case study

a) Case study description

The case study is a prototype single family house from the Sheikh Zayed Housing Program (SZHP). The SZHP is a federally funded housing program in the UAE that aims at providing adequate housing to its citizens. The case study is a two-storey single family house with a total area of (313 m²). The gross window-to-wall ratio (WWR) of this housing prototype is 14% with the highest WWR on the North façade (28%). Figure 1, and Figure 2 show the perspective, the ground floor, and the first-floor plans of the housing prototype respectively.
b) Case study energy model

An energy model for the housing prototype was created using DesignBuilder, a widely-used user interface for the simulation engine EnergyPlus [19]. The building envelope and systems were set to meet the minimum local code requirements for single family homes. The typical weather data for the city of Abu Dhabi in the UAE was used in the simulations. Natural ventilation was considered in the model by allowing window stay opened when outdoor air temperature falls within the range of 15 to 35°C. Figure 3 below shows the energy model created in DesignBuilder.

Figure 1. The SZHP housing prototype perspective [18].

Figure 2. The SZHP housing prototype (A) ground floor plan, and (B) first floor plan [18].

Figure 3. Energy model of the case study created using DesignBuilder.
3. Results

Observing the calculated TA of the base case model reveals that the indoor operative temperature is not within acceptable range (15 – 30°C) when the cooling system is not in operation for almost half of the year. Figure 4 shows a plot of the indoor operative temperatures of the base case model against the annual outdoor air temperatures. Only 4284 hours were within the habitable range with T\text{A}_{\text{base case}} = 0.49. This result indicates that this prototype could not sufficiently handle the consequences of an extreme heatwave in the absence of an active cooling system.

![Figure 4. Base case indoor operative temperature vs. outdoor air temperature](image)

![Figure 5. The calculated thermal autonomy (TA) for alternative simulation run of the case study](image)
Figure 5 demonstrates the calculated TAs for the eleven simulated models (base case + 10 alternatives). It is obvious that applying various passive EEMs affected the base case thermal resilience differently. For example, cases 1 and 2 (increasing the walls U-value) had almost no influence on improving thermal resilience. This could have happened because the base case level of insulation (U-value = 0.32 W/m2K) was adequate to handle conductive heat transfer through opaque walls which is limited compared to direct heat gains through windows.

While in cases 5, 6, 9 and 10, implementing passive EEMs (improving window properties in 5 & 6 and adding external fixed shading in 9 & 10) had a noticeable increase of the building thermal resilience. The number of hours within the acceptable operative temperature ranges has increased by about ~6.5 % with the windows properties upgrades and about ~8.2% when an external fixed shading was added for all windows. These improvements in TAs were because the upgraded windows and the addition of exterior shading devices reduced the amount of heat gain through windows and consequently reduced the number of overheated hours.

In cases 7 and 8 where infiltration rates were allowed to increase to 0.5 and 0.7 ACH, the TA was observed to improve as expected as any air movement/circulation and exchange with the outdoors would influence the indoor operative temperature. However, increasing the infiltration rate can lead to other consequences and can compromise the energy efficiency of the building.

4. Discussion

The evaluation of the thermal resilience of the energy model representing a housing prototype from SZHP in the UAE revealed that even though current minimum code requirements are sufficient in achieving short term energy efficiency goals, they are insufficient in achieving thermal resilience that is required to withstand extreme conditions that are becoming more frequent and harsher.

On another front, although typical weather data (which typically excludes extreme values) was used in simulations, the building was inhabitable once the outdoor temperatures reach or exceed 35°C. This indicates that buildings with their existing designs/conditions will struggle to handle extreme heat waves especially when it is coupled with power outages. It also indicates the need to consider future weather files for evaluating building performance as suggested by Berardi and Jafarpur [20]. Therefore, there is an immediate need to reassess the minimum requirement for housing design and construction to consider thermal resilience.

The study also examined the effect of implementing passive EEMs on the thermal resilience of the housing prototype. Overall, implementing single EEM, in its best cases, had limited improvement to TA which emphasizes the findings of the study by Ji et al [13] who concluded the need to implement multiple design strategies to improve/achieve resilience in buildings. It is also in line with the findings of the study by Sun et al. [4] which demonstrated that passive EEMs can improve thermal resilience to some extent but need to be coupled with some active strategies such as on-site power generation and thermal storage to reach safe building operation conditions.

Therefore, to build upon the findings of this study and comprehensively assess the housing prototypes of SZHP, future research should consider the following:

1. Conduct an optimization process that tests combinations of a wider range of EEMs.
2. Conduct simulations using future weather data to account for the increased frequency and severity of weather events, and
3. Develop new metrics that can express thermal resilience in a building in a more specific way. For example, develop metrics or indicators that can quantify resilience in buildings’ specific zones or per occupant.
5. Conclusions

In this paper, the thermal resilience of a housing prototype in Abu Dhabi, UAE was evaluated using thermal autonomy as an indicator. The evaluation was conducted through a simulation-based investigation of an energy model. The Thermal Autonomy was calculated for the simulated base case model using operative indoor temperature and the acceptable habitable operative temperature range was selected to be 15 – 30°C. The results indicated the need to improve thermal resilience of the housing prototype as the existing condition yielded a TA of 0.49 which indicates that half of the hours in a year are thermally inhabitable. Therefore, energy efficiency measures were applied to the base case model to improve the Thermal Autonomy. Ten alternative models of the base case were created and simulated. The TA was then calculated for each alternative model. The results revealed that window-related energy efficiency measures were the most influential in terms of improving thermal resilience. Recommendations were made thereafter to continue the investigation and test the impact of measures when combined into a single model.

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Conflicts of Interest: The authors declare no conflict of interest.

References


Identification of parameters for assessing the Livelihood Impacts of Dam-Induced Resettlement

Abstract: Dams have emerged as critical catalysts for economic development and clean energy production. However, their construction often leads to controversies due to the multifaceted impacts imposed on neighboring communities. Notably, the displacement and resettlement of affected communities remain paramount concerns, historically affecting millions of individuals. Consequently, there is an imperative to comprehend and alleviate the adverse social consequences of dam-induced resettlement. This research focuses on identifying key parameters for assessing the livelihood impacts resulting from dam-induced resettlement. Through a comprehensive synthesis of existing frameworks and in-depth case studies, the study meticulously examines the effects of dam-induced resettlement on affected communities. By analyzing relevant literature and frameworks, a comprehensive array of parameters and sub-parameters is delineated, enabling a thorough evaluation of the impacts. The findings offer valuable insights to guide future research and inform policy formulation, with a specific emphasis on minimizing the detrimental consequences associated with dam-induced resettlement and promoting sustainable development. Ultimately, these findings substantially contribute to an enhanced understanding of the social implications of dam projects, facilitating well-informed decision-making and the implementation of effective mitigation strategies.

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Keywords
Dam-induced resettlement; Livelihood impacts; Displacement; Resettlement; Social implications; Community participation; Indigenous communities; Policy implications
1. Introduction

Dams and their associated reservoir areas have emerged as vital sources of hydropower and water supply on a global scale, contributing significantly to economic development and reducing reliance on fossil fuels. However, the construction and operation of dams have also resulted in substantial resettlement of populations, known as dam-induced resettlement [1]. Dam-induced resettlement carries profound and enduring impacts that span across social, economic, and environmental dimensions, profoundly affecting the lives of affected communities. Socially, the loss of cultural heritage, disruption of social networks, and community upheaval are observed. Economically, individuals experience the loss of property, livelihoods, and income, often leading to increased poverty and food insecurity. Environmental consequences encompass the loss of fertile land, deforestation, and the degradation of wildlife habitats, among other ecological disruptions [2]. Criticism has been directed towards dam-induced resettlement due to inadequate compensation, insufficient planning, and limited engagement with affected communities resulting in persistent poverty, marginalization, and social unrest among resettlement populations. As a result, there is a pressing need to comprehensively evaluate the multi-faceted impacts of dam-induced resettlement, considering various aspects of livelihood [3].

The primary objective of this study is to identify parameters for assessing the livelihood impacts of dam-induced resettlement. The research involves a meticulous review of various frameworks used in previous studies, investigates three specific dam resettlement cases to identify common and significant parameters and sub parameters that contribute to the overall impacts on affected communities. The identified parameters can also aid in the development of frameworks and methodologies for evaluating the social consequences of dam projects, enabling informed decision-making and policy formulation ultimately promoting sustainable development practices and facilitating the implementation of effective mitigation strategies [4].

2. Materials and Methods

A comprehensive review of existing frameworks and studies related to dam-induced resettlement was conducted to identify parameters for assessing social consequences. The selected literature provided various frameworks used in these studies, which were critically analyzed to extract relevant parameters. In-depth analysis was performed on three specific dam resettlement cases, considering geographical diversity, representative examples, and reliable data availability. These cases yielded valuable insights into the impacts of dam-induced resettlement on affected communities. Data collection involved document analysis, including official reports, articles, books, and project documents. The collected data were carefully analyzed to identify common and significant parameters and sub parameters that contribute to the overall impacts of dam-induced resettlement. These parameters, mainly focusing on social aspects, were further categorized and refined based on their relevance and frequency of occurrence in the selected case studies. The findings from the literature review, framework analysis, and case studies were synthesized to create a comprehensive list of parameters and sub parameters.
3. Results

3.1. A comparative analysis of frameworks
The Sustainable Livelihoods (SL) Framework provides a holistic approach to poverty reduction and sustainable development, focusing on livelihood assets, activities, and outcomes. The Impoverishment Risks and Reconstruction (IRR) model specifically addresses risks associated with development interventions, including dam-induced resettlement. The Resettlement Framework (RF) guides the planning and implementation of resettlement programs, particularly in the context of dams. The SL Framework offers a comprehensive and adaptable approach applicable to various development contexts, while the IRR model is more focused on identifying and mitigating negative impacts of development interventions. The RF specifically addresses resettlement programs associated with dams. However, implementing the SL Framework can be challenging in resource-constrained settings, and the IRR model may not fully capture the complexities of impoverishment. The RF may have limitations in assessing long-term impacts and livelihood sustainability. livelihoods [5-7].

3.2 Parameters identified from Framework
The parameters used in Resettlement Framework (RF) and Integrated Resettlement and Rehabilitation (IRR) are identification of affected population: demographics (age, gender, ethnicity, etc.), livelihoods and income sources, housing and property rights, social networks and community relationships. Assessment of impacts: loss of assets and livelihoods, displacement and resettlement, access to resources and services, changes in income and expenditure levels, changes in health and well-being [8]. Design and implementation of resettlement and rehabilitation measures: resettlement options and plans, financial compensation and support, livelihood restoration and diversification measures, housing and infrastructure provision, access to education, healthcare, and other services, environmental rehabilitation and mitigation measures, participation and consultation of affected communities and Monitoring and evaluation: implementation of resettlement and rehabilitation measures, outcomes and impacts on affected communities, feedback and complaints mechanisms, continuous improvement of resettlement and rehabilitation measures [9].

The parameters used in the Sustainable Livelihoods (SL) Framework are Livelihood assets: natural resources (land, water, forests, etc.), financial resources (savings, loans, insurance, etc.), physical capital (tools, machinery, equipment, etc.), human capital (skills, education, experience, etc.), social capital (networks, relationships, community support, etc.). Livelihood strategies: agricultural activities (cropping patterns, livestock, etc.), non-agricultural activities (wage labor, small business, etc.), natural resource use (fishing, forestry, etc.), migration (temporary or permanent), diversification and adaptation to change. Livelihood outcomes: livelihood vulnerability and resilience, poverty and inequality, food security and nutrition, health and well-being, environmental sustainability, political and social empowerment, cultural heritage and identity and Contextual factors: policies and governance, infrastructure and services, environment, time and change, perceptions and attitudes [10].

3.3 Case Studies
The case studies conducted examine the impacts of dam-induced resettlement on communities affected by prominent dams, including the Sardar Sarovar Dam, Three Gorges Dam, and Tehri Dam.
3.3.1. Case Study 1: The Sardar Sarovar Project, India

The Sardar Sarovar Project (SSP) in India led to the displacement of approximately 200,000 individuals, predominantly farmers, fishermen, and Adivasi tribes, from the submergence zone of the Narmada River. The project aimed to generate 1,450 MW of power and provide water to multiple regions. It significantly impacted around 45,000 families from 192 villages in Madhya Pradesh, 33 villages in Maharashtra, and 19 villages in Gujarat. In response, the Sarovar Punarvasvat Agency (SSPA) established approximately 200 resettlement sites, including Sathod (Gujarat), Sathod (MP), Dhaliwara, Thuvavi, and Sinor-2, to accommodate the affected tribal communities such as Raathwa, Tadvi, Vasava, Dungri Bhil, and Bhilala. To comprehensively assess the impacts of dam-induced resettlement on local livelihoods, a study was conducted in Vadodara in 2015 [11]. A total of 167 households across five resettlement locations were surveyed to gain insights into the changes in livelihood experienced by the resettled population. One key area of impact was land ownership. Following relocation, there was a significant improvement in land ownership rights, with 157 out of 167 households having agricultural land registered under the name of the family leader. [12]. However, the ever-expanding families of tribal resettlers faced challenges due to the finite nature of land resources, limiting their ability to fully utilize and develop their allocated land. Agriculture emerged as the primary source of income for the resettled communities, supplemented by minor forest produce, fishing, and animal husbandry. The traditional economic importance of minor forest produce, such as bamboo for construction and the production of various goods, has diminished in the resettlement areas due to scarcity of raw materials, a lack of market opportunities, and decreased interest among the younger generation. Furthermore, the study revealed significant gender disparities in the impacts of dam-induced resettlement. Women, who had previously relied on forests for income and resources, experienced a severe reduction in access to forests and income from forest products. Prior to resettlement, more than 40% of female respondents contributed 50% or more to the household income. The loss of women’s control over resources and livelihood opportunities not only affected their economic independence but also had far-reaching implications for gender dynamics within the tribal resettler communities [13-15].

3.3.2. Case Study 2: Three Gorges Project, China

The Three Gorges Project in Yichang, Hubei Province, China, aimed to generate hydroelectric power, regulate floods, and enhance navigation. However, it resulted in the displacement of approximately 1.3 million people, making it one of the largest dam-induced resettlement projects worldwide. A survey conducted between 2004 and 2012, along with in-depth interviews, examined the impacts of resettlement on livelihoods. The study focused on income changes, savings and borrowings, employment opportunities, expenditure, and food security. Regarding income, the Zigui rural resettlement site experienced a significant increase of 440%, but average incomes across all resettlement categories declined compared to pre-resettlement levels after six months. Between 2003 and 2011, there was income growth, with all migration categories catching up to Yichang city dwellers. Nonetheless, the relocation groups, particularly rural individuals moving to cities and those in Badong County, remained at a disadvantage compared to urban residents. Savings and borrowings revealed that debt levels increased significantly between 2003 and 2011, while average savings remained at half of pre-migration levels. The share of households with savings slightly increased, but borrowing imposed significant hardships, offsetting the income gains. Employment opportunities shifted over time, with a decrease in the proportion of households engaged in physical labor and agriculture. At the project’s peak in 2003,
32% of families were involved in physical labor. However, with the completion of the project, employment patterns changed. Many households faced challenges in meeting their expenses, particularly among those resettled in Badong compared to Zigui. Rural-to-urban households earned less than rural-to-rural households, resulting in insufficient income to cover their expenditure. Food security increased after resettlement, but it remained higher than pre-resettlement levels, reflecting lower incomes in rural-to-urban and urban-to-rural households. Additionally, rural households’ ability to produce their own food played a significant role in mitigating food insecurity. The relocation process resulted in the loss of land, livelihoods, and social networks for many individuals. The loss of agricultural and fishing areas reduced food security and led to lower incomes and increased poverty. Disruption of social networks and community cohesion affected the mental health and access to resources and support systems for resettled individuals. Insufficient compensation for lost houses and livelihoods left many without financial resources to rebuild their lives and businesses [16-18].

3.3.3. Case Study 3: The Tehri Hydro Power Project, India

The Tehri Hydro Power Project, developed on the Bhagirathi River, led to the submergence of the entire urban population of 'Old Tehri Town (OTT)'. The Tehri dam created a reservoir that inundated OTT and around 125 villages, displacing 50,000 to 100,000 people. The Tehri Hydro Power Development Corporation (THDC) undertook rehabilitation efforts, dividing them into urban and rural rehabilitation. Urban rehabilitation focused on restoring the displaced families from OTT to a new town called 'NTT'. All 5,291 OTT families were completely rehabilitated under this initiative. However, some challenges were encountered during the resettlement process. Approximately half of the Project Affected Families (PAFs) expressed apprehension about relocating to new resettlement areas due to a lack of career and business opportunities, as well as insufficient supportive services and infrastructure. Dissatisfaction among PAFs stemmed from reduced wages and limited market and commercial prospects in the new location.

Challenges faced in urban resettlement zones included a lack of drinking water, unemployment, reduced and delayed remuneration, inadequate public transportation, limited business and market prospects, disconnection from other regions, and transportation facilities. Despite these challenges, there were positive outcomes observed after rehabilitation. Newly established restored colonies demonstrated improved infrastructure, including buildings, playgrounds, sanitation, drinking water, ventilation, and furniture. Property ownership increased, particularly with land up to 0.5 acres, and the market price of the new land exceeded that of the old land. PAFs who were rehabilitated in urban centers benefited from engaging in various economic activities, such as running stores and farming, leading to increased employment and income levels. They also had access to job opportunities in industries, services, transportation, and other urban fields. However, the Tehri Dam resettlement also resulted in negative impacts on the affected population. Loss of income and livelihood opportunities were common due to the displacement from their primary sources of income, inadequate compensation, and the disruption of social networks. The displacement also led to the loss of cultural heritage, limited access to resources like water and land, housing and infrastructure issues, health problems, and political marginalization [19-21].
3.3.4. Case Study 4: Livelihood impacts from case studies

The Impacts on Livelihood in Sardar Sarovar Dam Resettlement are loss of land and property, lost access to sources of income, loss of agricultural fields and fisheries, inadequate compensation, reduced income, lack of employment opportunities, loss of social and cultural identity, feelings of isolation and alienation, increased stress and mental health issues, increased exposure to environmental risks.[22-24].

The Impacts on Livelihood in Three Gorges Dam Resettlement are Loss of agricultural land or fishing rights, unemployment, decline in economic stability, transition to new sources of revenue, breakdown of social networks, reduction in access to necessary resources, social isolation, reduced community cohesion, loss of community’s cultural identity, loss of traditional activities, inadequate or inferior housing, overcrowding, poor sanitation, political marginalization, less access to health care, less access to education.[25-28].

The Impacts on Livelihood in Tehri Dam Resettlement are Financial hardships, disintegration of social networks, disintegration communities, loss of cultural heritage, loss of religious sites and cultural monuments, poor quality or inadequate housing and infrastructure, increased stress, depression, and other health problems.[29-32].

3.4 List of Identified parameters and sub parameters from Literature and case studies

Final list of identified parameters and sub parameters for assessing the livelihood impacts of Dam induced Resettlement on communities are as follows:

1. Socio-economic status: Demographics, employment, income, household expenditure, education, health, housing and infrastructure, and social networks.
2. Livelihood assets: Natural resources, financial resources, physical capital, human capital, and social capital.
3. Livelihood strategies: Agricultural activities, non-agricultural activities, natural resource use, migration, and diversification.
4. Impacts of resettlement: Loss of livelihood assets, displacement, loss of access to resources, changes in livelihood approaches, changes in income and expenditure, changes in health and healthcare access, and changes in social relationships.
5. Outcomes of resettlement: Livelihood vulnerability and resilience, poverty and inequality, food security and nutrition, health and well-being, ecological preservation, empowerment and social inclusion, and cultural heritage.
6. Policy and governance: Resettlement policies and regulations, policy enforcement, community representation and participation, transparency and accountability, and access to information and justice.
7. Infrastructure and services: Access to basic services, transportation and communication infrastructure, market and financial services, and recreational and cultural facilities.
8. Environment: Ecological impacts, water regime changes, land use changes, biodiversity and wildlife, natural hazard exposure and risk, and climate change impacts.
9. Time and change: Short-term, medium-term, and long-term impacts, continuity and change in cultural practices, and intergenerational effects.
10. Perceptions and attitudes: Community perceptions and attitudes, local authority and stakeholder perceptions and attitudes, and societal perceptions and attitudes.
4. Discussion

The study’s results have substantial implications for the field of dam-induced resettlement, enriching the existing knowledge base. The findings underscore the diverse impacts on livelihoods and shed light on the challenges faced by communities affected by dam projects. Examining case studies of prominent dams such as the Sardar Sarovar Dam, Three Gorges Dam, and Tehri Dam, consistent patterns emerged, including the loss of land and property, inadequate compensation, reduced income, and social dislocation. These findings emphasize the urgent need for comprehensive and context-specific measures to effectively address these challenges. The broader implications extend to policy and practice in dam development and resettlement, emphasizing the significance of considering the social and cultural dimensions when planning and implementing dam projects. Preserving cultural identities, restoring livelihoods, and involving community participation are crucial for achieving sustainable and socially equitable outcomes. To further enhance our understanding, future research should explore strategies to strengthen community resilience, assess the long-term sustainability of resettlement efforts, and evaluate the effectiveness of various policy approaches.

5. Conclusions

The study emphasizes the importance of considering the broader implications of dam-induced resettlement and highlights the need for tailored interventions and policies. By integrating social dimensions into dam development and resettlement processes, we can strive towards more sustainable and inclusive outcomes that prioritize the well-being and livelihoods of affected communities.

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References

and resettlement.


Abstract: One of the main phenomena associated with urban climate is the development of heat islands, whose effect can be intensified with climate change in episodes of heat waves. To increase urban resilience improving outdoor thermal comfort conditions, urban shadings can be provided on the places most exposed to sunlight. Although widely used in vernacular cities in warm climates, these devices have largely disappeared from modern cities. This theme was then rescued in a course dedicated to the study of solar geometry in the Architecture and Urbanism undergraduate program at the Federal University of Minas Gerais, Brazil. This paper aims to present the process and practical results developed by the students for a street in the city of Belo Horizonte. The teaching methods encompassed content about solar geometry in Architecture, searching for solutions and construction materials. The students tested the proposed devices on the sun path simulator (heliodon) using scaled physical models; virtual models were also tested in the software Sketch-up®, free version. The simultaneous use of physical and virtual models contributed to the maturation of the students’ spatial vision regarding the sun path and shadows, as well as the theme showed them opportunities to develop new types of urban furniture with environmental comfort function.
1. Introduction

Several aspects influence the urban climate such as [1]: location, relief, population density, traffic and industrial pollutants, human activities, presence or absence of green areas, solar orientation of the streets, among others. There are also noticeable differences in the microclimatic conditions in diverse areas of the city due to heat island effects. Therefore it is clear that thermal comfort within a densely populated city is impaired by the above factors. A number of strategies can be adopted to improve local thermal comfort and health conditions as, for instance, the use of cool surface materials, high albedo surfaces, permeable paving, evaporative cooling, vegetation and shading, including shading structures [2].

Urban shading structures have been used since vernacular settlements, however fell into disuse with modernist urbanism and artificial cooling of buildings [3]. They can be defined as devices whose function is to improve thermal comfort in places that receive too much solar radiation throughout the day, providing shade and protecting against unwanted sunlighting. These urban devices can be awnings or sun sails, trellises or mashrabiyas over the streets, arcades over the sidewalks or they can be an isolated element as urban furniture; some of them can even receive shrubs and vines. Recently we can see a revival of urban shading devices [4-5] as a countermeasure to urban heating, in order to control direct solar incidence, not only improving thermal comfort in streets but also allowing for building energy saving.

In informal urban areas, which make up about 20% or more of the urban fabric of large Brazilian cities [6], narrow and winding streets make it difficult to fit infrastructure, so that tree planting for shade in these kinds of streets is often not feasible. Nevertheless due to the high construction density these areas can present temperatures as high as in dense, vertical urban planned centers [7-8], causing thermal discomfort for residents and pedestrians. Therefore an alternative to street afforestation should be considered.

In this context, an elective studio course on environmental comfort focused on solar control was offered in the second semester of 2022 to undergraduate students at the School of Architecture in the Federal University of Minas Gerais. This course dealt with applications of solar geometry for the design of shading devices both for buildings and for urban environments. Topics addressed were: (a) characteristics of solar radiation on buildings and in the cities, bringing historical and vernacular aspects; (b) design of shading devices using sun path diagrams and sundials in mockups; (c) use of design aid softwares and (d) practice in designing an urban or a building solar shading device considering potential materials.

This paper presents one of the projects developed during the course by a student team that chose to work on developing an urban shading solution for a typical street in an informal settlement.

2. Materials and Methods

A methodology for a project practice was organized in the following steps: (a) readings and study on solar geometry and thermal comfort; (b) definition of the type of shading device to be designed; (c) selection of a real case for analyzing problems, potentials and device installation studies; (d) materials definition for construction of the device; (e) design and production of physical and virtual models of the device, and finally (f) testing of the physical device model on the heliodon and/or of the virtual device model in the software SketchUp© free version. Such steps were fundamental for designing a product linked to the place and using available materials thereby achieving adequate efficiency for the intended application.
2.1. Study area

The area chosen for the study is in the Estrela D’Alva neighborhood, a conurbation region between the municipalities of Belo Horizonte and Contagem, in the state of Minas Gerais, Brazil (figure 1). This region was identified as one of the most vulnerable to climate change in the city of Belo Horizonte [9], having a stable nucleus of heat throughout the year.

The student team researched the study area to select a street for intervention, taking into account the characteristics pointed out in literature for thermal discomfort: densely built and sealed area, little vegetation cover, east-west street exposed to solar radiation for most of the day and year. Porto Seguro street, typical of informal settlements, was selected.

2.2. Data processing

Starting the development of the urban shading device required some cartographic information. The topographic map of the municipalities was used to measure the widths of the street and its sidewalks, as well as to locate the buildings. It was found the street width along the selected section varies between 2.20 m and 2.60m and the sidewalk measures are between 0.40 m and 0.60 m. These measures confirm that street afforestation for shading is unlikely in Porto Seguro street since it would compete with the power and lighting poles, and other urban infrastructures (figure 2).

Figure 1. Location of the city of Belo Horizonte, state of Minas Gerais, Brazil and the urban fabric of the study area and surroundings of the Porto Seguro street. Source: Images Google 2023© CNES/Airbus, Maxar Tech., modified by the authors.

Figure 2. The last stretch of the Porto Seguro street: (a) CAD draw based on Belo Horizonte data sets and (b) a Google© street view image in March 2023. Source: the authors.
2.3. Shading device material and conception

The shading device concept aimed at: (a) not to block daylighting, only filtering out direct sunlight; (b) to allow the street ventilation, thus not producing air flow resistance; (c) to have some connection to the community. The use of pet bottles as material for the shading device was suggested by the instructors since it fits the necessary transparency and there is an existing recycling group in the neighborhood. The student team then used this material, as it is low cost and available locally. Furthermore the recycling group could transform plastic bottles into a more profitable product, like the shade device, and the local recognition and ambience could promote more zeal and maintenance by the residents.

The student team also designed several device modules at different heights and tilts, one partially overlapping the other, because they thought that a single device large enough to completely cover the street would probably obstruct the wind. From this stage on the students followed some principles of biomimetics [10]: leaves and flowers were taken as reference, being recognized as models for the use of clear and green plastic bottles when mounting the device mesh; the transparency of the plastic also refers to leaves which do not block sunlight completely.

2.4. Mockup and solar blockage tests

A physical scaled model of the shading device installed in a stretch of the street was built to be tested on the heliodon, a tool that simulates the apparent (local) movement of the sun across the sky vault at any latitude. This tool is very useful to aid students and professionals to better understand solar geometry and assess shading and sunlight patterns on buildings or in urban areas.

The model was built using materials similar to the proposed pet bottles. Cellophane paper was chosen to replace the bottles in order to mimic the transparency, plastic texture and the flexibility of the shading devices designed as awnings. The houses’ façades, as surfaces for fixing the devices and observing the shadows, were made of thick cardboard. The façades of the street section were painted as place references. Finally the tensioned awnings were affixed to the “walls” using double-sided tape, following the pattern installation designed using a CAD software. Figure 4a,b shows the physical model. The model was placed North oriented for testing on the heliodon.

![Figure 3](image_url)
3. Results and Discussion

3.1. Shading device design and assembly

Seven 250 ml pet bottles were used for mounting the device mesh prototype (figure 4c). The bottles were cut to use only their bottom parts whose form is similar to a flower - these parts were painted to highlight this shape. To connect the cutouts small holes were made on all six sides of each one then joining them using cotton string. Students suggested bamboo fiber for the real project instead of string as it is highly resistant and a sustainable material. This assembled set forms a mesh whose module is a tensioned awning. The modules can be fixed to the façades by means of metal hooks.

The awnings were drawn on the street map to better measure their lengths and overlaps. In figure 5a one can observe the areas of transparency and overlap. After deciding where each module would be fixed and defining their limits and sizes the model was imported into the software SketchUp© free version to get a better spatial view of the intervention (figure 5b). SketchUp© is capable of simulating the local sun path and shadows by using the “shadows” tool in mode “use sun for shading” and set to the city’s standard meridian.

3.2. Mockup tests on the heliodon

Figure 5 shows the sequence of tests carried out for the scaled model on the heliodon. The photos record some times of day for the summer solstice (December 22nd), the equinoxes (March 21st and September 23rd) and the winter solstice (June 21st) for the latitude of Belo Horizonte (20° South). The student team could then study the shadows and the effectiveness of the designed device.

Figure 4. Installation section of the Porto Seguro street: (a) areas of awnings studied using a CAD software; (b) spatial view of the shading devices installation. Source: the authors.
One can notice in figure 5 that the awning modules performed well in terms of design, decreasing direct sunlight throughout the year on the street. In addition, they also cast shadows on the façades oriented northeast (at the right side of the images) between the equinoxes and the winter solstice - on the summer solstice these façades will be in self-shading during most of the day. Southwest façades also benefit from shading especially in summer (at the left side of the images). Differences in module tilt allow the sun rays to enter at certain times of the day in addition to not blocking the street ventilation. The improvement of the street comfort conditions by the shading device needs yet to be tested in future works by means of simulation of the thermal conditions.

Based on this experience some learnings can be pointed for future opportunities. Among them, the following can be mentioned: (a) the course, as it is short-term (only 30 hours), should be reorganized to achieve more dynamic, compelling activities. Due to time limits the theoretical part should be reduced then allowing the expansion of practical activities including the making of physical models by all teams; (b) the students suggested more emphasis on the devices design process using sun path diagrams and other tools; (c) an opportunity is to extend the practice time on the heliodon with short exercises about "brise-soleils", light shelves and urban shading devices, including scaled models tests during the class period, encouraging the "learning by experience"; (d) the partnership between instructors from architecture and product design broadened the knowledge and practical experience on developing the shading devices, detailing materials and installation aspects; (e) it is also possible to develop models in different scales such as 1:5; 1:10; 1:20... for a better study about constructive details and performance tests on heliodon.

5. Final remarks

During the development of this study, three important moments were identified by the student team: firstly, the making of the model and the mesh prototype led them to reflect about logistics and the use of materials, as well as to explore the potential of biomimicry for a meaningful design. Then, the shading device solution revealed several possibilities of use and different forms that it could assume. Finally, the tests on the heliodon gave them an idea of how the device would behave throughout the year.

The design research process showed the relevance of environmental comfort issues and how they can influence aspects of a place that would be conventionally difficult to change. However, the limited time to develop the practice brought challenges in data survey, since visiting the site, accessing...
historical data and the residents opinions were not possible. Thereby, the work was based just on images, maps and previous reports.

Relating to urban shading devices, it is important to consider the availability of materials and the location in which they will be installed. In this sense, the existence of a recycling group in the neighborhood could be a potential to use a material for creating local identity, adding value to discarded bottles and generating a sense of belonging for residents.

Bearing all this in mind, the students have learned to value aspects of the environmental comfort approach that previously would not receive much importance or would not even be considered by them. They now think about studying this theme as fundamental for the education of an architect, and when designing an urban shading device they “consider themselves able to let their creativity flow, create, develop and remake according to their vision of beauty and efficiency”. Perhaps the best result for the instructors is that the student team now see this kind of approach as a “fun and relaxed journey to study something as significant for our quality of life as environmental comfort”.

References


Author Contributions: Eleonora Assis and Fernando Silva are the instructors and advisors; Bruna Rodrigues, Enzo Costa and Julia Valadares are the student team who developed the device concept and design, the physical and virtual models and carried out the tests on heliodon. The student team prepared the draft paper and images, and the instructors reviewed, edited and translated the paper into English.

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Exploring the Potential of Urban Agriculture in Villas: A Study of Green Spaces and Gardening Practices in the UAE

Abstract: Urban farming is becoming increasingly important globally, as 68% of the world’s population is expected to live in urban areas by 2050. Urban farming offers several advantages, including access to fresh food, reduced transportation costs and emissions, job creation, economic opportunities, and can also foster social interaction and community engagement. In the United Arab Emirates (UAE), the government has recognized the importance of food security and launched initiatives to increase domestic food production. Hence, this study aims to identify the existence of green space in individual housing and users’ practices, perceptions, and behaviors in the context of urban agriculture in villas in UAE, characterized by very large plots of lands. An online survey was conducted to ascertain the characteristics of green spaces, the type of plants, usage, and practices, as well as gardening practices and challenges faced by respondents. The findings revealed that a significant proportion of respondents (94%) resided in villas where green spaces were present in varying degrees, serving predominantly aesthetic (63%) and shading (64%) functions. Interestingly, only 32% of respondents engaged in fruit and vegetable production for personal use. The maintenance of green spaces was largely outsourced to hired gardeners, and daily irrigation was primarily carried out using a hose (65%). The upkeep cost of the garden was not known to most respondents (74%). These results provide important insights into the utilization and management of green spaces in residential settings. The low percentage of respondents engaging in urban agriculture indicates a need to better understand, promote and encourage such practices. This information can be used by different stakeholders to develop programs and initiatives that promote and support urban agriculture.

Keywords
Urban farming, Garden, Villas, Greenery, Survey, Food production, Users’ perception, Challenges, Hot climate, Urban resilience, United Arab Emirates.

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1. Introduction

The United Nations Development Program (UNDP) stressed the growing worldwide importance of urban farming, as almost 70% of the world population is expected to be living in urban environments by 2050 [1]. In the increasingly urbanized environment of the United Arab Emirates, like global trends in many developing countries, natural ecosystems are often threatened [2]. Globally, the social and environmental agenda are dominated by sustainability goals, with eco-cities being a prime research and planning focus. Ecological approaches in planning for sustainable cities [3] stress the role of nature in the urban environment [4]. It is well known that plants have a role in several ecological processes in urban settings. They improve environmental quality, mitigate the negative consequences of human presence, and improve human health and wellbeing. The quality of urban life is a natural consequence of the way people interact with the urban environment [5]. Therefore, environmental quality becomes a fundamental building block of social well-being and urban quality of life. Greenery and public open spaces are a significant element of the urban environment that contribute to quality of life [5-7]. In parallel, increasing interest has focused on food security and food production in the built environment [8-9] with an acknowledgement of its benefits transcending economic contribution [10-11] to include social and environmental benefits [12-13].

The food security global agenda calls for increasingly revisiting how our cities are shaped, while exploring their potential contribution to food security and its additional multidimensional benefits. Urban farming does present its own set of challenges such as 1) Access to land, where urban farmers often face challenges in accessing land due to limited availability, high costs, and competition with other land uses such as housing, commercial development, and infrastructure projects [14], 2) Policy and regulatory challenges: Urban farming may be subject to zoning restrictions, health and safety regulations, and other legal barriers that can limit its expansion and sustainability [15], and 3) Social and cultural barriers: Urban farming may face resistance from some community members who view it as a nuisance or a threat to property values, as well as cultural barriers to its adoption in some communities [16].

In this regard, while community farming is often explored for its numerous benefits, the kitchen garden and kitchen farming in the context of the UAE has not been explored fully yet. A kitchen garden is a space where produce is cultivated for home consumption, such as fruits, vegetables, or herbs. This is particularly relevant knowing that villas with large plots of land compose a large portion of the urban fabric (Figure 1, a). Despite the anecdotal report of an increasing interest to include organic food production in their backyard, especially among those who live in large plot villas [17], only one study carried by Degefa et al. (2021) explored the homestead food production system’s characteristics in the UAE, its importance for ensuring household food security, and pinpointed the variables that influence families’ participation in home food production [18]. The study identified the potential of urban farming in UAE and linked its potential growth to more awareness. Aspects such plot size, open space design and users’ perception and behavior regarding kitchen garden have not been explored.

Over the past four decades, the United Arab Emirates (UAE), the context of this study, has experienced remarkable population and economic growth, fueled by its substantial oil revenues. This rapid expansion has led to a significant surge in urbanization, like many other fast-growing economies. Between 2005 and the end of 2021, the population of the UAE surged from approximately 4.1 million to an estimated 10 million. Amongst this significant increase, the number of UAE citizens accounted for around 1 million individuals [19]. Given the resources of the UAE, traditionally the government allocated a plot of land for building a house and a plot for farming. These were characterized by large plots, often exceeding 1000 square meters. Currently, most of the population (over 85%) lives in urban settings [20]. For example, in Al Ain city, an oasis city, dominated by low density, low rise residential buildings, even current social housing includes very large plots of lands (Figure 1 (a)). There is a large area of land that can serve the dual purpose of recreating the original biodiverse ecosystems of the oasis while also potentially contributing to food security and adding greenery to the urban landscape. However, a visit to some residential areas quickly reveals their poverty in vegetation, engendering cause to effect interrogations on the impact of houses.
plot size, typology and occupants’ attitudes and practices towards vegetation and food production and its perceived role and value in everyday environment (Figure 1 (b)). There is therefore a need for an investigation and documentation of the green space and kitchen farming practices in villas as well as a need for an understanding of the specific practices associated with alternative food initiatives, its perception, users’ behavior, and the challenges encountered.

Hence, this paper presents the first part of a more comprehensive study that aimed to identify first the materialization of greenery and inclusion of food production practices, if any, in urban villas, along an exploration of users’ perception, behavior, and practices in relation to the green space and kitchen garden within their home.

![Figure 1 (a). New development in Al Ain city; Villas with large plots of land and their potential to include urban farming.](image1)

![Figure 1 (b). Lack of greenery in individual villas with large plots.](image2)

2. Methodology

The aim of this study was to investigate the presence of green areas within villas, their usage patterns, and the potential for food production. Additionally, the study sought to understand how residents engage with these spaces, the maintenance practices employed, and the challenges or limitations associated with promoting sustainable food production in urban environments. To gather empirical evidence regarding the existence and factors influencing urban farming, a survey was designed. The survey consisted of six sub-sections, covering various aspects related to demographic data, home characteristics, garden specifications, garden practices, and urban farming, encompassing the following:

1. Demographic Data; or the participant’s identification category including age, gender, working status, nationality, location within the country and length and where among the seven emirates does the recipient live

2. Home characteristics; included questions on home type (villa, townhouse, or apartment), ownership, and length of stay in the house.
3. Garden specification; checked the presence of a garden, its locations (front, back and or sides), explored the type of vegetation, identified by type of trees, grass, decorative plants (flowers and shrubs) other green trees, Fruits and vegetables and fake grass.

4. Gardening practices; explored the role of the garden (usage of outdoor sitting, for aesthetic reasons, shading, and the produce some fruits and/or vegetables), highways, edges, and vistas) that are important in the collective memory.

5. Garden maintenance; checked the role of the respondent if any in the maintenance of the garden as an inquiry into the engagement, the type and frequency of irrigation, as well as the cost of upkeeping of the green part of the home.

6. Urban Farming explored the ownership of an urban farm owned, its proximity to the main residence, usage, production and consumption of produce.

Prior to the main survey, a pilot study was conducted with a small group of participants (n=7) to test the survey instrument and make necessary adjustments. Based on the feedback received, questions were reformulated, sub-question sequences were reorganized, and Arabic translations were added for each item. Additionally, illustrative images were included to enhance clarity and minimize potential confusion, particularly regarding irrigation methods. Ethical approval for the survey was obtained from the UAE University Ethical Review Board, with approval number ERSC_2023_2667, in April 2023. The distribution of the survey started on April 23, 2023, and continued for a duration of 5 weeks. Various channels were utilized to reach potential participants, including the UAEU official email, university student’s WhatsApp groups, and university student’s Telegram groups. These distribution channels were chosen to maximize the likelihood of reaching Emirati nationals residing in villas, considering that UAEU predominantly serves this population. A total of 110 voluntary responses were received during the data collection period. However, only 90 complete responses were considered for the preliminary results presented in this research paper. By conducting the pilot study, obtaining ethical approval, and utilizing targeted distribution channels, the survey aimed to gather comprehensive and representative data on the characteristics of gardens and greenery in UAE villas.

3. Results

The survey was conducted over a duration of five weeks, after obtaining ethical approval, during the months of April and May. Out of the total number of respondents during that period, which was 110, only 90 complete responses were considered for analysis (N=90). The findings below describe the results obtained from the analysis of the complete responses following the six subsections addressed in the survey.

The characteristics of the survey’s respondents indicate a predominantly young to middle-aged population, with the majority falling between the age range of 21 to 50 years old. Among the respondents, 42% were aged 21-30, while 49% were aged 31-50. The survey attracted a significant number of female participants, accounting for 88% of the total respondents. Furthermore, the survey primarily targeted Emirati nationals, as they constituted 93% of the respondents. In terms of employment status, a substantial portion of the participants, approximately 65%, reported not being currently employed. This finding suggests that a significant proportion of the respondents were either unemployed, self-employed, or retired individuals.

The house characteristics section aimed to gather information regarding the housing typology,
location within the United Arab Emirates, and length of stay in the surveyed houses. The results revealed that most respondents resided in villas, which aligns with the target of the survey. Specifically, 94% of the respondents reported living in villas, indicating a high representation of this housing type in the study. The remaining respondents were almost equally divided between apartments and townhouses.

In terms of geographical distribution, the respondents were spread across the seven emirates of the United Arab Emirates. Among these emirates, there was a predominant representation from Abu Dhabi and Sharjah Emirates, accounting each for (48%) and 45% of the respondents respectively. Additionally, respondents from Abu Dhabi were split between two locations, with 24% residing in the city of Al Ain and another 24% residing in Abu Dhabi city (Figure 2).

![Figure 2. Map of the seven emirates within the United Arab Emirates and distribution of respondents per emirate.](image)

Regarding ownership status, a significant proportion of the respondents (75%) reported owning their homes. This finding indicates a higher prevalence of homeownership within the surveyed population. Furthermore, the respondents had been residing in their current homes for an extended period, with over 5 years being the most common duration of stay, suggesting a relatively stable residential situation for most participants.

The next series of questions addressed the existence of an outdoor garden and greenery in general within the respondent’s villa, the greenery location in relation to the house, its main usage, explored the type of vegetation, distinguishing between trees, flowers, and shrubs, as well as food producing plants. Most villas surveyed included some form of garden/greenery as expressed by 81% of the respondents. The greenery was mainly located to the front of the house (50%) and/ or on the sides (43%). Only 14% identified it as located to the back of the house. The garden housed different types of vegetation including palm trees in over half of the cases (56%) along other types of green trees (38%) as well as fruit bearing trees (46%). Over 65% of the responses identified the greenery as decorative plants...
including flowers and shrubs, while natural grass was only available in 19% of the homes while artificial grass was present in 38% of the cases. In terms of food producing plants, it was reported in only 21% of the cases that their garden included some vegetable production (Figure 3).

The garden specification section focused on exploring the presence of an outdoor garden and greenery within the respondents' villas. It also investigated the location of the greenery in relation to the house, its main usage, and the types of vegetation present, distinguishing between trees, flowers, shrubs, and food-producing plants. The findings revealed that most of the surveyed villas (81%) included some form of garden or greenery. Among these, the greenery was predominantly located at the front of the house (50%) and/or on the sides (43%), while only a small percentage (14%) indicated its presence at the back of the house. The gardens in the surveyed villas encompassed various types of vegetation. Palm trees were found in over half of the cases (56%), indicating their popularity in context. Additionally, other types of green trees were present in 38% of the villas, while fruit-bearing trees were found in 46% of the cases.

![Types of vegetation in your garden](image)

**Figure 3.** Types of plants found in the surveyed villas.

When considering the purpose of the greenery, many of the respondents (over 65%) identified it as primarily consisting of decorative plants, including flowers and shrubs. Natural grass, on the other hand, was available in only 19% of the surveyed homes, whereas artificial grass was present in 38% of the cases, indicating its usage as an alternative to natural grass for landscaping purposes (see Figure 3).

In terms of the role and usage of the gardens, the survey results indicated a dual purpose for aesthetic reasons and as spaces for sitting and enjoyment. Around 30% of the respondents mentioned the shading role of the gardens, highlighting their importance in providing relief from the intense heat. Furthermore, approximately 36% of the respondents reported that their gardens served the purpose of producing fruits and vegetables for personal consumption (Figure 4).

The maintenance of green spaces was largely outsourced to hired gardeners, with 75% of the
Figure 4. Role and usage of the garden in the surveyed houses

respondents relying on external assistance for garden upkeep. In terms of irrigation practices, approximately 65% of the respondents reported using a hose for daily irrigation. Drip irrigation systems were present in 37% of the cases, while sprinkler systems were employed by 16% of the respondents. It is worth noting that most respondents (74%) were unaware of the exact cost associated with maintaining their gardens.

Additionally, the survey explored the presence of urban farms near the surveyed houses. The findings revealed that 50% of the respondents had access to an urban farm located nearby. These urban farms were primarily utilized to produce fruits and vegetables, fulfilling the family’s own consumption needs.

4. Discussion

The findings from the survey regarding the presence and characteristics of gardens and greenery within the surveyed villas in the United Arab Emirates (UAE) and its hot climate, provide insights into the specific context of residential gardening practices in the region and how residents adapt to the challenges posed by its extreme hot climate.

The high prevalence of gardens or greenery in the surveyed villas (81%) aligns with the importance placed on outdoor spaces in the UAE, where residents often seek to create pleasant and inviting environments despite the hot climate [21]. Gardens serve as a means to connect with nature, enhance aesthetics, and create shaded areas that mitigate the effects of high temperatures [22]. The presence of greenery contributes to a sense of coolness and improved microclimates within residential areas [31].

The location of greenery predominantly at the front and sides of the houses reflects the consideration of aesthetics and curb appeal. In the UAE, there is a cultural emphasis on presenting well-maintained front yards, as they play a role in social interactions and community identity [24]. The limited presence of gardens at the back of the houses may be attributed to privacy concerns, functional use of space, or the availability of larger outdoor areas in the front or side [25].
The popularity of palm trees in the surveyed gardens aligns with their suitability for hot climates and contextual identity. Palm trees have adapted well to arid regions and can withstand high temperatures and limited water availability [26]. Their presence provides shade, aesthetic appeal, and cultural significance, reflecting the connection between greenery and the local context.

The preference for decorative plants, including flowers and shrubs, over natural grass aligns with the need for water-efficient landscaping strategies in hot climates like the UAE. Water scarcity is a significant concern, and residents often opt for low-water-use plants that can thrive in arid conditions [27]. The presence of artificial grass further reflects the desire for green spaces without the maintenance requirements and water consumption associated with natural grass [28-29].

The relatively lower proportion of gardens with food-producing plants (21%) may be influenced by several factors. The UAE relies heavily on food imports, and growing food in home gardens may not be a common practice for self-sufficiency [30]. Additionally, the availability of fresh produce in local markets and the challenges of gardening in a hot climate with limited water resources may contribute to the lower prevalence of food production in residential gardens.

5. Conclusion

This study aimed, though a survey, to provide insights into the presence and dynamics of urban farming in the context of residential environments (villas) in the united Arab Emirates (UAE). The findings of this survey provide valuable insights into the prevalence, characteristics, and role of gardens and greenery within the surveyed villas. The results highlight the residents’ adaptation strategies to create and maintain green spaces in a hot climate, taking into account factors such as water scarcity, aesthetics, and cultural preferences. The dominance of decorative plants and the popularity of palm trees reflect the residents’ inclination towards creating visually appealing environments within their villas. The presence of other types of green trees and fruit-bearing trees adds to the diversity of vegetation, contributing to the overall aesthetics and functionality of the gardens. The limited presence of natural grass and the higher adoption of artificial grass suggest the residents’ consideration of water conservation and the desire for low-maintenance alternatives. The reliance on hired gardeners for garden maintenance highlights the availability of a cheap workforce. The presence of urban farms near the surveyed houses indicates the maintenance of traditional urban agriculture and localized food production.

In summary, these findings underscore the multifaceted role of gardens in the UAE, encompassing aesthetics, leisure, shade provision, and, to a lesser extent, food production. The residents’ adaptation strategies, reliance on hired gardeners, irrigation practices, and engagement with urban farms contribute to the broader understanding of residential gardening and urban agriculture in the unique environmental, cultural, and climatic context of the UAE. While these insights inform on the current gardening characteristics, further investigations are needed to better understand the reasons and challenges with food production in the studied context.
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References


11. Cameron, J., Wright, S. 2014. Researching diverse food initiatives: from backyard and community
garden to international markets. Local Environ. 19:1–9. [Taylor & Francis Online], [Google Scholar]


through green infrastructure in the hot dry city of Abu Dhabi. Sustainable Cities and Society, 38, 574-585.


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CHAPTER 2
Sustainable Architecture
Abstract: Construction is commonly seen as an industry with low efficiency and productivity. Offsite construction is presented as a potential way to improve construction efficiency and has been promoted by the UK government recently, which has been encouraging the adoption of Modern Methods of Construction. In offsite construction, the production of modules allows them to be almost completely made inside a factory, leaving only the installation and the finishes between modules to be done on-site. However, the adoption of offsite modular construction has seen only marginal increases and the standardization of designs is one of the possible reasons for that. To improve this scenario, companies could use the strategy of mass customization. Nonetheless, not all companies are prepared or want to use this strategy, due to their business models. Therefore, it is necessary to know how existing companies are acting in the market to offer customization. In this sense, the objective of this study is to promote a discussion of how the business model influences customization in the United Kingdom through case studies of companies operating in different sectors and installed in several regions of the country. The research indicates that companies have very different business models, which influence the offer of customization. Different competitive strategies imply the specific use of technologies and choice of the production process. Several factors are interconnected and essential for offsite modular construction companies to remain competitive in the market.

Keywords
Offsite construction; modular construction; customization; business model.

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1. Introduction

The construction industry is commonly seen as a low-innovation industry, with a history of non-compliance with schedules and budgets, high waste of resources and numerous accidents at work. It presents high complexity and low efficiency and productivity [1]. Offsite construction presents itself as a potential way to improve construction efficiency. It can present benefits in relation to production on site, such as independence from weather conditions, reduction in construction time, waste, costs, and increased safety, quality, productivity and environmental performance [2-4].

Goodier and Gibb [5] define offsite construction as the fabrication and pre-assembly of building components, elements, or modules before installation in their final locations. The literature on offsite construction subdivides it in different ways [6-8]. Boyd et al. [8] subdivide offsite construction into offsite pre-assembly, which corresponds to the production of construction components, materials and equipment, such as trusses, stairs and precast elements; hybrid systems, which represent fully prefabricated units with complete finishes, such as bathrooms and kitchens; panelised systems, which represent the use of prefabricated structural framing systems, such as doors, windows, cladding and timber structures; and modular buildings, which correspond to multiroom units that include finishes and installations, such as complete houses and apartment blocks. Nahmens and Reichel [9] observed that modular construction makes it possible to carry out a higher number of activities in the factory, compared to other categories, reducing the work time on the construction site and, therefore, was chosen as the focus of this study.

The United Kingdom has a long history of using modular construction, therefore it was chosen as the appropriate location to carry out this research. In the country, modular construction was applied to deliver houses after the First and Second World Wars [10, 11]. In 1998, the British government report “Rethinking Construction” [12] defined objectives for construction improvement that included the use of offsite construction, addressed under the term “Modern Methods of Construction”. More recently, in 2017, the British government adhered to a series of measures to improve the cost, effectiveness, productivity and delivery of housing works, further promoting the adoption of modular construction. Currently, the country has more than 200 companies that carry out this type of construction [13].

However, despite the benefits, over the years the adoption of offsite construction has seen only marginal increases, which may have several reasons, such as its association with low-quality temporary buildings [14], the previous unsuccessful examples [15] and the negative perceptions of many customers, which are due to the high degree of standardization necessary to reduce unit costs in the economy of scale [16]. However, the consultancy Bryden Wood [17] believes that conditions are now favorable for a change in the construction industry.

In terms of flexibility, the tendency to repetition has been highlighted in offsite construction [18]. Polat [19] and Jaillon and Poon [20] indicate that design variations are less frequent in offsite construction due to transport limitations that end up restricting module sizes, generating less product diversity and design innovation [21]. Therefore, Halman, Voordijk and Reymen [22] state that companies need to apply concepts that allow greater customization, while ensuring low unit costs and high product quality [23].

In this sense, mass customization (MC) is presented as a business strategy that provides customers with a range of product options, based on their needs, with costs and delivery time like those achieved in mass production [24, 25]. The implementation of MC, however, is still a challenge [26], because it requires manufacturers to be ready to change products and their manufacturing processes efficiently. MC requires stable but flexible and responsive processes, which are achieved through innovative product and process designs, including digitization and automation [27].

Not all modular construction companies are prepared to offer MC, and some are not interested in adopting this strategy, as product design affects production processes [28]. Jonsson and Rudberg [29] and Duncheva and Bradley [30] recognize, in their articles, the differences and particularities between offsite construction companies. Jonsson and Rudberg [29] created a model that relates the different spectrums of offsite construction (components, non-volumetric systems, volumetric systems and modular buildings) to the customization offer. However, no work was found that relates the
business model of modular construction companies, considering their particularities, with the customization offer.

Therefore, the objective of this work is to promote a discussion on how the business model influences customization of modular construction in the United Kingdom, considering the relation between the particularities of companies and the ways in which they offer customization. According to Pan and Goodier [31], despite the growing academic interest in offsite construction, additional studies are needed at the organizational level as opposed to the study of individual projects.

2. Materials and Methods

As a research method, multiple case studies were carried out that aimed to understand the strategies used by modular construction companies in terms of construction systems, organization of the production process, customization offer for customers and level of mechanization in the factory. From the information gathered, it was possible to identify similarities and differences between the companies. Through the case study, an understanding of the contemporary phenomenon and its practices in its natural context is created [32]. Case studies of 6 English modular construction companies were carried out between June and December 2022. They included factory visits and interviews with managers from different areas. Below, it is possible to see a summary of each of the companies that participated in the case studies.

**Company A:**
operates in the educational, commercial and housing sectors. When the case study was carried out, the company manufactured 100% bespoke products and had approximately 100 employees. The construction system used consisted of a steel structure and steel frame for the envelope and internal partitions. The company had a low level of mechanization and a production system based on fixed modules.

**Company B:**
operates in the housing sector. At the time the case study was carried out, the company manufactured 100% bespoke products and had approximately 100 employees. The construction system used consisted of a structure, envelope and internal partitions in timber frame. The company had a low level of mechanization, and the production system was in transition between fixed modules for the implementation of a production line.

**Company C:**
operates in the housing sector. When the case study was carried out, the company used the strategy of MC, offering 9 options for houses, and had approximately 800 employees. The construction system used consisted of a steel structure and steel frame for the envelope and internal partitions. The company had a medium level of mechanization and a production line system.

**Company D:**
operates in the health, construction, industrial, commercial and educational sectors. At the time the case study was carried out, the company manufactured 100% bespoke products and had approximately 45 employees. The construction system used consisted of a steel structure and timber frame for the envelope and internal partitions. The company had a low level of mechanization and a production system based on fixed modules.
Company E:
operates in the health, construction, industrial, commercial and educational sectors. At the time of the
case study, the company had several product lines with the MC strategy and had approximately 3000
employees. The construction system used consisted of a steel structure and timber frame for the
envelope and internal partitions. The company had a high level of mechanization and a production line
system.

Company F:
operates in the housing sector. At the time the case study was carried out, the company used the MC
strategy, offering 29 options for houses and apartments, and had approximately 700 employees. The
construction system used consisted of a structure, envelope and internal partitions in timber frame. The
company had a medium level of mechanization and a production line system.

It is noteworthy that the level of mechanization was divided into three categories: low, medium and
high. Companies with a low level of mechanization have machines for cutting timber or steel, and there
is a need for employees physically involved in the operation of these machines or in the operation of
manual equipment (such as drills). Companies with a medium level of mechanization have, in addition
to machines for cutting timber or steel and manual equipment, CNC lathes for carrying out some
operations that generally include cutting timber or plasterboard, connecting parts or materials, and
milling. CNC lathes involve programming and operation by an employee who is not physically
involved in the operation process, only in the process of feeding the lathe (placing materials in the
correct position). Companies with a high level of mechanization, in addition to the equipment
mentioned above, have robots performing some activities such as welding and painting. Regarding the
production process, fixed modules are considered to be the process in which the modules remain in the
same place during all production stages, with materials and employees moving around each of the
modules. In the production process called production line, each stage of production has a determined
place in the factory to happen and the modules move along the factory, going to the next stage (next
station of the line), in which the materials that will be used are already available and the worker is
prepared to carry out specific activities.

One of the limitations of the research is related to the method used, as case studies can make it difficult
to generalize the results. Another limitation is the number of case studies carried out, since the
restricted number of case studies also limits the generalization of the results. Thus, it is suggested the
realization of other case studies in different countries, to confirm the results obtained in the present
study.

3. Results

According to Da Rocha [33], the context of each organization plays an important role in defining the
customization strategy to be adopted: the application of the MC approach and related principles must
be aligned with the strategic objectives and processes of an organization. This statement was
corroborated by this research, in which case studies it was possible to observe different strategies used
by English modular construction companies to offer customization, depending on the companies
business model.

Through the case studies, it was possible to note that companies that present flexibility as a
competitive strategy (such as companies A and D) generally focus on offering 100% customized
products, bespoke for each customer. As projects are not repeated, companies in general have
difficulties in formulating process indicators that measure productivity. In addition, these companies
have great flexibility between the amount of work that is carried out in the factory and on the construction site, depending on the complexity of the project and the manufacturing demand. Companies focused on flexibility usually have a production system based on fixed modules, with low mechanization. The workforce must be qualified and is a fundamental part of ensuring the delivery of projects with the desired quality.

In the opposite case, companies that present productivity as a competitive strategy (such as companies C, E, and F) generally focus on offering mass customized products, so that the customer chooses among the options available in a product catalog. As projects are repeated, companies have different productivity indicators and seek continuous improvement. In addition, these companies do as much work as possible inside the factory, leaving only the connection between modules to the construction site, which reduces project delivery time and improves final quality control. Companies focused on productivity usually have a production system based on a production line, with medium or high mechanization. The workforce is not qualified and product quality is guaranteed through standardized processes.

There are also companies that operate halfway between the two competitive strategies presented above, seeking to offer flexibility and productivity at the same time (Company B is an example of this). These companies usually focus on offering 100% customized products, buy-sell only in large quantities. The large quantities and feature repetitions of materials and the production process, allow companies to formulate productivity indicators. In addition, these companies have great flexibility between the amount of work carried out in the factory and on the construction site, depending on the complexity of the project and the manufacturing demand. Companies focusing on both flexibility and productivity usually have a production system based on a production line, with low or medium mechanization. The workforce must be qualified and is a fundamental part of ensuring the delivery of projects with the desired quality.

For companies that seek to offer both flexibility and productivity or for those that have flexibility as a competitive strategy, customization has a great influence on productivity, since the greater offer of different products means that employees must learn to perform new activities frequently. That way, productivity is lower than it would be if employees performed the same activity repeatedly. Thus, the greater the customization offered, the lower the productivity of the factory. However, in all cases, companies can offer the primary benefit of modular construction, which is the reduction of construction time at the construction site, which implies less indirect costs, lower variations in material costs and, consequently, lower risks.

4. Discussion

In offsite construction and especially in modular construction, there are many articles that show MC as the ideal solution for companies, such as the work of Jensen, Nielsen and Brunoé [34], which assumes that Danish offsite construction companies can benefit from the inherent advantages of using MC, or the article by Khalili-Araghi and Kolarevic [35], which deals with the automatic design for MC of houses produced offsite. These articles advocate the use of MC as it would ensure increased productivity, product quality and allow modular construction companies to continue to offer options at low unit costs [34, 35]. However, MC implies scale production and it is recognized that this is not necessarily the goal of all modular construction companies.

Pine, Victor and Boynton [23] emphasize that not all markets are appropriate for MC. Offsite construction companies that do not mass produce or mass customize can also exist in the market, if they use the appropriate business model, since, as shown by Jonsson and Rudberg [29], some companies went bankrupt due to not being able to properly link the production system with the level of customization they wanted to offer.

Through this research, it was possible to create a matrix that relates: the competitive strategy of offsite modular construction companies, the degree of customization they offer, the production system they use and the level of mechanization that such a system presents, as shown in Figure 1. This way,
companies that present flexibility as a competitive strategy offer pure customization, which means that companies should not invest in highly specialized equipment, since they produce many different types of products, thus, the production system will be in fixed modules and will have low mechanization. Examples of this are companies A and D studied during the case studies. Companies that have productivity as a competitive strategy must restrict their product offerings and product parts must be standardized, which implies the adoption of mass customization. For productivity to be achieved, companies must have standardized processes, with activities that are repeated, so that they can acquire machines that do repetitive activities. This implies the use of a line production system, with medium or high mechanization. Examples of this are companies E, C and F studied. Trying to achieve flexibility and productivity at the same time is the most complex competitive strategy and implies a customization offer that must give the customer ample possibilities of choice, but must also allow some repetition and standardization of production. Because the products still show great variations, the company should not make large investments in specialized machines, so that the level of mechanization of production will be medium. In addition, the company can adopt a mixed production system, in which part of the production is done in line and part in fixed modules, or choose, between these, the strategy that proves to be more appropriate for the variation on flexibility and productivity to be offered. An example of this is company B, studied.

Figure 1. Matrix that relates competitive strategy, degree of customization, production system and level of mechanization.

5. Conclusions

This work achieved the objective of promoting a discussion of how the business models influence the customization of modular construction in the United Kingdom, considering the relation between the particularities of companies and the ways in which they offer customization. This was possible through case studies with six companies of different sizes and areas of activity. Several factors are interconnected and are essential for modular construction companies to remain competitive. The research indicates that companies have competitive strategies that depend not only on the sector in which they operate, but also on their market niche. In this sense, modular construction companies present different business models, which influence the customization strategy.
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References

1. Vrijhoef R.; Koskela L. A critical review of construction as a project-based industry; identifying paths towards a project-independent approach to construction. In CIB Symposium, Combining Forces, advancing facilities management & construction through innovation series. 2005 (pp. 13-24). VTT.


9. Nahmens I.; Reichel C. Adoption of high performance building systems in hot-humid


26. Salvador F; De Holan PM; Piller F. Cracking the code of mass customization. MIT Sloan manag. rev. 2009.


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Abstract: The current conditions of Climate Change define our future steps in the building sector. It is our generation’s responsibility to improve the building design to reduce electricity consumption, therefore, to reduce CO2 emissions. Referring also to the SDG 11, UAE has made great effort in the green building sector. This study follows these efforts. The research will evolve in two parallel tracks referring to a hospitality building in Liwa, Western Regions. The methodology followed in this study is as below:
- Analyze the site selection (location, climate, microclimate),
- Design Concept based on UAE national tree.
- Modeling of proposed structures through python.
- Results

In conclusion, the aim of this study is to use the advanced tools available to explore the possibilities of design of residential and hospitality projects, considering all available parameters into designing structures that are environmentally, economically, and socially sustainable. The findings might help industry to integrate advanced tools in the early stages of design.

Keywords
hospitality project; national tree; active strategy; rhino; python

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1. Introduction

The article focused on the two case studies of Alexander Klein’s plan analysis model and Cedric Price’s research on housing through his concept of a 24-hour economic living toy. In both cases, work is done on the search for an optimal housing proposal, where Klein optimizes the form and Price optimizes the use. Both make use of recognizable parameters; therefore, their experiences are reproducible and replicable. In addition to the cases being analyzed using contemporary parametric tools to digitally reproduce the results of the analog diagrams developed by both architects. The work was carried out under a model of scientific thinking that today we can recognize as parametric thinking [1].

This work provides parametric and multi-objective optimization techniques in order to examine the daylight performance of the expanded-metal shading that represents the sky conditions in Kitakyushu, Japan. The research is an early design strategy that employs a reliable computational calculation to support expanded metal as an eco-friendly construction material in regard to its employment as a shading device. The suggested platform uses dynamic design variables like Bond, Strand, Length, Height, and Angle to generatively iterate the logic of expanded metal in order to maximize Spatial Daylight Autonomy, Useful Daylight Illuminance (UDI), and the openness of the expanded-metal profile while simultaneously minimizing Annual Sunlight Exposure (ASE). The goal was to confirm the competence of expanded-metal shading as an environmentally friendly building material in terms of daylighting by developing an integrated parametric-design platform and optimization processes repeating expanded-metal logic to optimize daylight objectives [2].

A growing approach in architecture is designing with biological materials, which calls for the creation of new design methods and fabrication techniques. This paper debates whether designers are able to use a parametric design approach when working with living materials. The study experiments with the parametric behavior of living systems using fungi as a biomaterial probe. Conducting the design experiments using fungi helped in determining whether biological systems can be parametric and, if so, the type of parametric systems they are [3].

This article demonstrates how parametric design may offer a solution to a number of intricate issues, such as urbanization and climate change. It mainly discusses how parametric design has switched from an esthetical approach to a problem-solving approach. Founded by Zaha Hadid, Zaha Hadid Architects is an architectural firm that has gathered information through in-depth research, digital design techniques like parametric design, and relations between elements in order to accomplish an integrated solution for challenging design problems. It was conducted that the designer should focus on two methods of designing during a design process to achieve a sustainable and socially healthy built environment for the future: environment-based design and society-based design. The advanced form-finding capabilities of parametric architecture make it an excellent platform for more 3-dimensional data analysis. “This offers the designer a better understanding of how the forces of nature and society work in complex forms and how to find relations between elements to achieve an integral design.” [4].

This study explores a more technical parametric design method by developing an architectural landscape planning and designing a method that integrates artificial intelligence parametric analysis, suitable for landscape design based on the characteristics of architectural landscape design. Its fundamental component is an improved particle swarm optimization (IPSO-BP) network, which receives architectural landscape garden-related parameters as input and generates outputs as garden planning and design plans. This network combines the Backpropagation (BP) algorithm with enhanced particle swarm optimization (IPSO), which can effectively improve network performance. It adopts a strategy to improve the particle swarm algorithm. This particle algorithm is improved to pass the local optimization test, and some particles are replaced to increase the diversity of particles. By doing this, the algorithm successfully avoids the difficulty of it falling into the local optimal value and maintains the best global particles of each generation. As a result, compared to the performance of the basic PSO algorithm, the global optimal value is much higher [5].

Computational design is the method of employing programming to design and alter forms and
structures. In this study researchers use bibliometric analysis, a method for providing a perceptible summary of massive quantities of scholarly research. To start, search data from Lens were exported and then examined with VOS viewer to determine the co-occurrence of specific keywords. It discusses different cases and how each is handled by computational design [6].

2. Methodology

The methodology followed in this study is as below:

- Analyze the site selection (location, climate, microclimate),
- Design Concept on basis of UAE national tree.
- Modeling of proposed structures through python.
- Results

2.1. Analyze the site selection (location, climate, microclimate)

The site selected for this project is located in the area of the Liwa in the Western Regions of Abu Dhabi. The location is approximately two hours drive from the capital. The area has an impressive landscape where dunes and oasis merge together. The area currently has several high-end resorts with a traditional Arabian design. The location was selected based on the criteria of having a place that would help mental wellbeing. This building design adapts to the location by respecting the terrain and following the sustainability principles [7].

![Figure 1. Liwa location in connection to Abu Dhabi.](image1)

![Figure 2. Location of the site in Liwa Oasis.](image2)
The United Arab Emirates is known for its tropical weather. The weather in Liwa, Abu Dhabi is hot and dry throughout the year, with temperatures ranging from 21°C in the winter to 48°C in the summer. Liwa experiences very little rainfall, with an average of just 3-4 rainy days per year. The area is known for its high humidity, which can make the hot temperatures feel even more oppressive. Despite the harsh weather conditions, Liwa is home to several natural attractions, including the Liwa Oasis, which is known for its stunning palm groves and ancient forts. Overall, the weather in Liwa can be challenging, but it is a fascinating and rewarding destination for those who are prepared for the heat and dryness [8].

2.2. Concept based on UAE national tree

The Ghaf tree which is also known as Prosopis cineraria is a native tree species found in the United Arab Emirates. It is a hardy, drought-resistant tree that can withstand extreme temperatures and can grow in a variety of soil types. In the UAE, Ghaf trees are often used as a natural windbreak and are an important source of shade in the hot desert climate. Ghaf trees are considered sacred by many people in the region, and they are often planted around homes and villages to provide protection. The trees are also a symbol of national pride and are featured on the coat of arms of the UAE. In recent years, there has been a concerted effort to plant more Ghaf trees in the UAE as part of a wider campaign to conserve and protect the country’s natural resources. These efforts have included large-scale planting initiatives and the establishment of conservation areas for the Ghaf tree [9][10].

The wellness center will be located in the Liwa desert, surrounded by spectacular dunes that work on relieving stress from the human’s body. The main concept behind the design was linking the traditional gaff tree of the UAE, mostly found in the desert, with the structure of the building. Gaff trees are renowned for their wide, spreading branches. Each branch spreads outwards from the tree’s trunk at an angle. We took this concept one step further by creating our own design for the wellness center. The design will embody the gaff tree’s leaves and branches in the middle of the desert, giving a spectacular paradise view from the top. The design will host separate rooms with private pools overlooking the dunes. The rooms will surround the public pool shaded with a wave-like pattern, found on the sand dunes. The design was separated into units to ease the modeling process, the rooms were modeled using Revit program, while the roof was modeled using Rhino and python language to create a parametric kinetic roof. Lastly, the units were grouped together to form the complete final design.

Figure 3. Conceptual development of the design.
Figure 4. Conceptual development of the project.

Table 1. Space distribution in the project.

<table>
<thead>
<tr>
<th>ID</th>
<th>LOBBY Dimensions</th>
<th>ROOMS ID Dimensions</th>
<th>SPA ID Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lobby</td>
<td>86.22</td>
<td>Room 35.7</td>
<td>Lobby 14.3</td>
</tr>
<tr>
<td>Male Toilet</td>
<td>3 Bathroom 13.6</td>
<td>Bathroom 5.4</td>
<td></td>
</tr>
<tr>
<td>Female Toilet</td>
<td>3 Planting 8.2</td>
<td>Spa Room 6.2 (3)</td>
<td></td>
</tr>
<tr>
<td>Caffe</td>
<td>38 74</td>
<td>Pool 24</td>
<td>Lockers 6.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deck 57.5</td>
<td>Sauna</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yoga Area 20</td>
</tr>
</tbody>
</table>

2.3. Modeling of proposed structures thru python.

The parametric kinetic roof and the wave-like shading structure for the public pool using Rhino Grasshopper and the Python programming language were successfully created. The parametric roof inspired from the leaves of the gaff tree, will be covering the rooms. The mind and body of a person experiences an unexplainable tranquility as they gaze at the many glittering stars in the dark sky. To allow the clients to enjoy stargazing, the roof was developed using Python to allow the dynamic movement of various components. When designing the roof, it was difficult to move all parts together, so to ease the process the script was divided into 3 repetitive parts. Each part will be assigned to move 1 part of the roof structure. The shading device on the other hand was also designed using the python language, however the script was simple in a way that it follows any given shape. The height, magnitude, and direction of the design can be easily controlled [11][12].

Figure 5. Conceptual development of the rooms roof in python.
Other difficulties encountered during the design of this advanced tool was the initial time consuming to adapt to the software, read all geometries, adapt to the terrain and different levels. Rhino with the new plug-ins was quite efficient in the later stage of the design [13].

3. Results

The research results are linked to the aim initially stated. Developing parametric structures for a hospitality project, wellbeing center in Liwa, UAE. Based on all the design processes mentioned above, in this project the scope of designing a sustainable wellbeing center based on advanced tools is achieved. The design adapts on the terrain and starts from the inspiration of the national tree. This makes the project environmentally and socially sustainable. The results are divided in two main parametric structures referring to the bedroom suites and the pool zone.

Parametric/Kinetic roof for the bedroom suites: The results show that the parametric kinetic (dynamic) facade of the rooms makes possible coverage from the sun during the day and opens during the night so the visitors can have a sky view. In the deep desert of Liwa the sky is very clear to be seen at night. Figure 7 shows this parametric/kinetic structure of the roof of the bedroom suites. as Figure 8 shows the same but with a closer look in order to capture the openings of the roof. Figure 9 shows interiors of the rooms with attention to the indoor plants and the view from the rooms, creating a good connection indoor-outdoor. This is an important point for the main function of the mental wellbeing center, where the calming effect of the dunes has a positive impact on the visitors.
Parametric Roof Design for the pool zone: This roof design is inspired from an imitation of the dune waves. The result shows a quite interesting and complex structure (fig.10,11). In addition, this structure is practical and flexible to be installed on the site. This parametric structure allows natural ventilation but, in the meantime, it brings shade to the external areas. The design is innovative and brings a connection between the pool zone and the surrounding dunes (fig.12, 13).
In order to show the positive impact in reducing the solar radiation thru the application of parametric structure a series of simulations with the calculation of the solar radiation were conducted for the main buildings designed. The Software of rhino/grasshopper gives a very clear visual of the solar radiation reduction before and after the applications of such structures. The evaluation is done for the characteristic days of equinox and solstice. Table 3 shows the Bedroom Suites Radiation Analysis; Table 4 shows the Reception building Suites Radiation Analysis; Table 5 shows the Swimming pool Structure Radiation Analysis.
Table 3. Reception building Suites Radiation Analysis

<table>
<thead>
<tr>
<th>Day</th>
<th>Jan 21</th>
<th>Mar 21</th>
<th>June 21</th>
<th>Sep 21</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Result with no shaded roof</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>Total result(%)</td>
<td>956.095</td>
<td>693.425</td>
<td>3063.072</td>
<td>1028.895</td>
<td>37451.662</td>
</tr>
<tr>
<td>Visual Result 30° east shaded roof</td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
<tr>
<td>Total result(%)</td>
<td>416.681</td>
<td>376.246</td>
<td>520.149</td>
<td>556.085</td>
<td>215316.266</td>
</tr>
<tr>
<td>% Reduction from Base case</td>
<td>36.12%</td>
<td>42.90%</td>
<td>64.09%</td>
<td>45.48%</td>
<td>45.52%</td>
</tr>
<tr>
<td>Visual Result Closed Shaded Roof</td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
</tr>
<tr>
<td>Total result(%)</td>
<td>526.503</td>
<td>279.109</td>
<td>394.157</td>
<td>391.931</td>
<td>195762.544</td>
</tr>
<tr>
<td>% Reduction from Base case</td>
<td>47.14%</td>
<td>57.88%</td>
<td>62.57%</td>
<td>61.01%</td>
<td>58.42%</td>
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</tbody>
</table>
Table 4. Swimming pool Structure Radiation Analysis

<table>
<thead>
<tr>
<th>Day</th>
<th>Dec 21</th>
<th>Mar 21</th>
<th>June 21</th>
<th>Sep 21</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Result with no shaded roof</td>
<td>1110.009</td>
<td>1163.331</td>
<td>1254.114</td>
<td>456532.879</td>
<td></td>
</tr>
<tr>
<td>Total result (kWh)</td>
<td>731.072</td>
<td>477.321</td>
<td>752.685</td>
<td>720.022</td>
<td>268492.040</td>
</tr>
<tr>
<td>% Reduction from base case</td>
<td>32.91%</td>
<td>40.58%</td>
<td>44.79%</td>
<td>42.93%</td>
<td>41.28%</td>
</tr>
<tr>
<td>Visual Result 90° open shaded roof</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total result (kWh)</td>
<td>794.703</td>
<td>428.116</td>
<td>653.386</td>
<td>648.722</td>
<td>288446.011</td>
</tr>
<tr>
<td>% Reduction from base case</td>
<td>31.33%</td>
<td>46.73%</td>
<td>59.56%</td>
<td>48.27%</td>
<td>42.78%</td>
</tr>
</tbody>
</table>
4. Discussion and Conclusions

The aim of this research was the application of innovative tools in a wellbeing center, hospitality project, in the depth of Liwa desert landscape of UAE. The tool used was rhino-grasshopper and the language used was python. This discussion refers to three main points:

- The tools applications: The project shows that the application of these tools in the early stages of design can help achieve a sustainable building through the parametric concept used. This connects the project to the terrain while maintaining a highly efficient building. However, these tools need prior extensive training, and the experimenting of such structures is time consuming.

- The development of a parametric/kinetic roof was challenging due to the curved shape of the roof. This shape was chosen to create a connection of the units with the surrounding environment as shown in figure 14. However, more work is needed in defining the solar radiation in the internal space during different times of the day and different seasons.

- The parametric roof of the pool zone: This structure was difficult to model since there are two layers involved. The addition of the second layer is done with the aim of increasing the standing at the pool base. However, more work is needed to test various innovative materials for achieving a lighter roof structure (fig.15).

   However, more work needs to be done also in evaluating the impact on the energy consumption in the internal space from the parametric/kinetic roof of the bedroom suites. In the second case of the parametric roof at the pool zone, additional study is needed to understand the impact of this structure.
in the outdoor thermal comfort. This research has several innovative elements, such as the application of advanced tools in early stages of design, creating innovative shapes and good connection of structures with the surrounding desert landscape.

Figure 14. Aerial view, closer camera, of the parametric roof of the pool zone.

Figure 15. Aerial view, closer camera, of the parametric roof of the pool zone.

In conclusion, the applications of advanced tools in early stages of design helps achieve a sustainable project while connected to the local architectural and social heritage. This study can be useful to the industrial design firms in similar complex projects in the region.

Autor Contributions V.I.: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “conceptualization, L. Bande.; methodology, L. Bande.; software, A. Alsheraifi, and Y. Asmelash.; validation, Y. Asmelash.; formal analysis, A. Alsheraifi, R. Alderei, E. Alwathali and Y. Asmelash.; investigation, L. Bande, A. Alsheraifi, R. Alderei, E. Alwathali and Y. Asmelash.; resources, L. Bande.; data curation, L. Bande.; writing—original draft preparation, L. Bande.; writing—review and editing, L. Bande.; visualization, A. Alsheraifi, R. Alderei, and Y. Asmelash.; supervision, L. Bande.; project administration, L. Bande.; funding acquisition, L. Bande.;”.

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Conflicts of Interest: The authors declare no conflict of interest.

References


Production planning and control in customized modular construction: design, manufacturing plant, and construction site integration.

Abstract: Mass customization (MC) is a strategy to increase value generation through the production of a variety of customized products while keeping costs and delivery time within acceptable limits. Although it is a relatively new business strategy in the construction industry, there has been a growing interest in MC, especially by companies that adopt modular integrated construction (MiC). In MiC, production is typically carried out offsite: building elements are manufactured in a factory environment and then transported to a site for final assembly and installation. It aims to reduce on-site labor and construction time, resulting in different types of benefits, such as cost reduction, reduction in project lead-time, productivity improvement, and reduction of waste, which contributes to construction being more sustainable. Despite its potential to minimize problems associated with the complexity of traditional construction practices, in MiC there is a different type of complexity to be managed as there is more interdependency between the design, manufacturing plant, and site installation. The aim of this study is to propose guidelines for integrating design, manufacturing, and site installation in modular construction systems through planning and control systems, based on lean production concepts. This is an ongoing investigation, and some preliminary results are presented in this paper. This study also aims to contribute to the body of knowledge on modular construction by understanding the nature of this process and the interactions between subsystems.

Keywords
Mass customization, Modular Construction; Construction Management; Lean Production, Last Planner System, Production Planning and Control (PPC)

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1. Introduction

Mass Customization (MC) combines the benefits of mass production while providing a broad variety of choices to customers with product costs or delivery times that are similar to mass production. Its goal is to deliver products that meet diverse requirements and demands in a specific market [1]. There has been a growing interest in the application of mass customization (MC) in the construction industry, largely attributed to the widespread adoption of modular construction [2]. By integrating modular construction with the MC strategy, companies in the construction industry can effectively offer personalized products while keeping a high level of efficiency.

In this context, product modularity plays a crucial role in supporting mass customization by enabling the creation of customizable units without significantly disrupting the production process, which in turn contributes to increasing the perceived value of the product [3]. Modularity is the ability of a system to be subdivided into smaller, independent, interconnected modules, which are assembled following standardized rules [4]. Gibb [5] defined modular construction as the production of three-dimensional (3D) units to enclose functional spaces, forming a completed building. In the current context, Pan and Hon [6] address this concept of Modular integrated Construction (MiC) as a ground-breaking and highly innovative approach that contrasts with the conventional fragmented and site-based construction of buildings and facilities. MiC is a process that integrates value-driven production and assembly of prefinished modules, offering the potential for enhanced quality, productivity, safety, and sustainability. Industrialized building systems may be more sustainable than conventional construction, notably due to higher quality, adaptability to change without demolition, reduction of waste, minimized disturbance to the vicinity of the site and reduction of the embedded energy brought about by using simpler processes [7].

However, through the lens of Pan and Hon [6], in modular construction complexity needs to be managed, especially in terms of managing stakeholders, as MiC involves different manufacturing units which supply components to different construction sites, sometimes involving costly logistics operations [5,8]. Based on the definition of complexity proposed by Williams [9] and Saurin and Gonzalez [10], it can be assumed that modular construction reduces the complexity of the construction site by reducing the number of activities to be performed, the number of personnel required, and the diversity of resources involved. Additionally, it contributes to managing variability within a more controlled production environment (i.e., the manufacturing plant), reducing uncertainties and interdependencies between activities. This enables the distribution of responsibilities and the management of complexity among various stakeholders, leading to a more effective management system. However, a different type of complexity is created by the fact that manufacturing plants and design teams must meet the demands of multiple projects, coordinate requests from various suppliers, and adhere to tight deadlines. Therefore, an appropriate management model is necessary to address these challenges faced by modular construction systems.

The high degree of interdependence between production units in the MiC system demands much exchange of information, even more so than in conventional construction projects. This exchange of information becomes even more critical when the degree of product customization is high. In this context, the concept of pull production proposed by Hopp and Spearman [11] should be adopted: factory production must be triggered by the status of the system, i.e. planning must consider the variability that exists in construction site activities. This approach helps work-in-progress (WIP) control while ensuring that only the necessary components are delivered to the site. To implement this strategy, near real-time information about production status is required.

Some construction companies that work with customization projects have unique solutions for modular projects, which results in an increased lead time required to meet deadlines since these are not standardized solutions for the product. When the project development stage occurs simultaneously with production, it increases the level of complexity even further in both the factory and construction site environments. In addition to these factors, clients may also request adjustments in design, which further adds complexity to the production of modular components. Ultimately, a significant amount of rework may be generated due to the poor transition between the design and production stages.
Considering the importance of managing complexity in customized modular construction projects, there is a need to integrate Project Planning and Control (PPC) across design, manufacturing, and site installation. Therefore, the aim of this study is to propose guidelines for integrating design, manufacturing, and site installation in modular construction systems through planning and control systems, based on lean production concepts. This is an ongoing investigation, and some preliminary results are presented in this paper. This study also aims to provide contributions to the body of knowledge on modular construction by understanding the nature of this process and the interactions between subsystems.

2. Research method

Design Science Research (DSR) was the methodological approach adopted in this investigation. In DSR, knowledge is developed directly by deeply engaging with real-life problems or opportunities [12]. The main outcome of DSR is an innovative artifact, also named a solution concept, that solves a class of problems and simultaneously provides a prescriptive theoretical contribution [13]. The artifact that is being developed in this investigation is the integrated planning and control model.

The study had three phases: (i) understanding the problem and its real-work context, (ii) development and implementation of an integrated production planning and control model through an empirical study, and (iii) analysis and reflections of the findings. The literature review was developed during the entire research process.

The first phase aimed to gather general data from the company, including the planning and control systems used in the design, manufacturing, and construction site units. Based on those data, improvement opportunities were identified for each planning and control system, based on the requirements identified for each production unit.

In the second phase, each planning and control system was improved, based on Lean Production concepts and principles, especially on the adaptation of the Last Planner System and Location Based Planning and Control. The research team closely monitored the implementation of these systems, which included some necessary adaptations of planning and control tools to the context of modular construction.

The third phase involved a discussion and assessment of the first version of the model. This was carried out in a workshop involving the research team and company’s representatives. During this event, the researchers presented the model that describes the interfaces between the planning and control processes of the design, factory, and construction site. Discussions focused on information exchange, interactions between sectors, and the necessary interfaces between planning and control systems, as well as the means of communication used (meetings, spreadsheets, emails, etc.) and the information flows. Furthermore, through these discussions, it was possible to grasp the challenges and difficulties faced by each sector in terms of information exchange. The outcome of this stage was an integrated model that describes the interactions and interfaces between the three planning and control systems.

The study was undertaken in a Brazilian modular construction company, named Company A. This company is located in southern Brazil, and has two manufacturing plants. The main focus of Company A is the prefabrication and assembly of modular components for prisons and schools, offering customized solutions for each construction project, by adapting modular products to the client’s needs. The largest manufacturing plant was the focus of this investigation, in which construction modules are assembled and finished, serving multiple projects. It is important to highlight that each project has an independent planning and control system and its own management team for site installation, while the design team, and manufacturing plant have to generate information and produce modules for multiple projects.

Triangulation was employed as a strategy to enhance the reliability and validity of the research findings by using multiple sources of evidence. This approach involved collecting data from various perspectives and sources, in order to get a comprehensive understanding of the phenomenon under
investigation. This study included (i) direct observations of two construction sites and one manufacturing plant; (ii) participant observations in weekly medium and short-term meetings; (iii) semi-structured interviews with those involved in planning and control; (iv) analysis of documents related to PPC, such as spreadsheets, indicators, and projects; (v) participation in workshops undertaken with representatives of different sectors; and (vi) meetings with company’s representatives to discuss the planning and control models being implemented. The sources of evidence used in this study are presented and detailed in Table 1. Data collection began in August 2022 and is still ongoing.

<table>
<thead>
<tr>
<th>Source of Evidence</th>
<th>Direct Observation</th>
<th>Participant Observation</th>
<th>Semi-structured Interviews</th>
<th>Document Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>2 visits to the design sector in the company; 5 meetings to develop the model; 2 kick-off meetings with internal and external designers; 5 medium and short-term meetings with all designers;</td>
<td>5 meetings to develop the model; 2 kick-off meetings with internal and external designers; 5 medium and short-term meetings with all designers;</td>
<td>Planning coordinator and assistant; Manufacturing manager; Continuous improvement coordinator;</td>
<td>Project schedule; Design segmentation map; Medium-term and short-term plans; Master list of projects deadlines;</td>
</tr>
<tr>
<td>Manufacturing plant</td>
<td>10 visits to the modular production and assembling factory; 1 long-term meeting; 3 medium-term meetings; 4 short-term meetings;</td>
<td>1 long-term meeting; 3 medium-term meetings; 4 short-term meetings;</td>
<td>Planning coordinator and assistant; Manufacturing manager; Continuous improvement coordinator;</td>
<td>Long-term, medium-term, and short-term plans; Modules assembly activities’ check-in and check-out database;</td>
</tr>
<tr>
<td>Construction site</td>
<td>4 visits on site of project A; 58 medium-term meetings;</td>
<td>58 medium-term meetings;</td>
<td>Project A and B engineer; Planning coordinator;</td>
<td>Line of balance; Medium-term plans; Short-term plans;</td>
</tr>
</tbody>
</table>

| Table 1. Sources of evidence |

3. Results

Three different planning and control systems have been developed for the company, one for each sector, all based on similar concepts and principles. They strongly emphasize the need of managing uncertainty and variability, such as in LPS, and are based on the idea that location, i.e. a module, is a planning and control unit. Moreover, similar to LPS, three different hierarchical levels have been used: long-term, medium-term, and short-term planning. Figure 1 provides an overview of the proposed integrated model for production planning and control for modular construction, with a particular focus on pull production.

Figure 1 is divided into three main subsystems for MiC, representing the planning and control systems of each sector, while logistics serves as the link between the manufacturing plant and the
construction site. To depict the connections between different planning levels, arrows with gradient colors ranging from black to light gray are used. These connections are numbered from 1 to 4 and are described below. The main discussion focus is on the interfaces between these sectors.

![Diagram](image.png)

**Figure 1.** The integrated model for production planning and control in modular construction

The interactions between the long-term planning levels of different sectors are visually represented by arrows numbered 1. The long-term plan of the construction site should drive the production in both the manufacturing plant and the design sectors. Therefore, all three long-term plans need to be aligned. The bidirectional nature of the arrows implies that the definition of the construction site’s long-term plan depends on the production capacity of the manufacturing plant and the design sector. It is also important to note that both factory and design sectors need to consider the demands of multiple projects. Thus, the long-term plans of the manufacturing plant and design sectors must also be aligned with each other to ensure the production of modules. Therefore, the long-term plan of the factory should pull the production in the design sector and needs to be confirmed by this sector according to its capacity.

The interactions between the second level of the hierarchical system planning are represented by arrows that have the number 2. Those arrows show the interaction between the medium-term planning levels of the different sectors and constraints or confirmation points that trigger activities at this planning level in other sectors. These are some examples:

- A confirmation point between the factory and construction site, which may occur four weeks before the on-site installation of modules. This interaction between sectors provides information that confirms, in the factory’s medium-term plan, the modules that will actually go into production;
- A constrain identified in a medium-term meeting of the construction site or the factory that can inform the medium-term plan of the design sector or request adjustments;
The dotted arrows represent potential constraints or information exchanges presented by the design or manufacturing plant sectors during the medium-term meetings of the construction site of each undergoing project. These meetings provide an opportunity for all stakeholders to exchange information about the progress of their activities, understand the status of the project, and communicate any difficulties or necessary constraints for task development. Therefore, the interaction between the manufacturing plant and the design also occurs during site installation medium-term meetings.

The representation of arrow 3 shows the information that the prefinished modules are already assembled or in stock in the manufacturing plant, ready to be installed at the construction site. This information arises at the short-term planning level of the factory.

Lastly, arrow number 4, which occurs in both directions, represents (i) the confirmation point between the construction site and the logistics sector for module installation, enabling the development of the expedition plan, and (ii) the final confirmation point that allows the loading of the modules. This information flow is connected to the short-term planning level of the construction site.

It is worth mentioning that the feedback of information mainly occurs during the managerial meetings of the construction site, particularly during the medium-term meetings, which play a crucial role in facilitating the integration between sectors. Based on that feedback, the managerial team of each unit gets relevant information to improve internal processes and exchange valuable insights to support decision-making processes, so that the overall performance of the production system can be achieved.

4. Discussion

An initial set of guidelines for integrating the production planning and control systems of the design, manufacturing plant, and construction site sectors in modular construction has been proposed. These guidelines are based on the literature review, and particularly on the findings of the empirical study undertaken in Company A.

1. Adopt a decentralized production planning and control approach. This management approach involves collaborative and two-way communication between different units, coordinated by managers and carried out by actors with some degree of autonomy [14], instead of centralizing planning in one person. This task is assumed collectively by representatives of different units, increasing the sense of ownership and collaboration.

2. Work on pull production based on a decentralized yet integrated planning system with well-defined confirmation points. Design and factory production should be planned to be pulled by multiple projects. For this purpose, the plans of each sector should be aligned from their long-term levels. Additionally, points of confirmation are important to deal with system variability, one to release the manufacturing of modules and another to authorize the loading of modules for delivery on site, as also utilized by Bataglin et al. [15].

3. Conduct a kick-off meeting upon contract closure. It is important to have a kick-off meeting amount sector coordinators as soon as a new contract is closed to facilitate the alignment between the long-term plans of all the sectors. In this way, the sectors can develop their own plans based on the same contract assumptions and deadlines, and this defines solutions to meet the project demands. The long-term plans must then be checked and revised, and it is expected that major adjustments will not be necessary, contributing to deal with the short lead time of the system.
4. Adopt Location-based Planning and Control. This approach facilitates the monitoring of the production status of each sector and the information exchange between them. The use of the line of balance is recommended, along with the adoption of production status matrices for each sector. Production status matrices are developed based on information about check-in and check-out activities' date.

5. Implement Visual Management tools. In order to support system transparency and facilitate information exchange between sectors, dashboards can be utilized. These dashboards provide relevant information for the interface between sectors, allowing for easy access and visualization of indicators, progress status, and other relevant data.

6. Facilitate collaboration among the different sectors. Collaboration occurs when two or more individuals come together to achieve a common goal, sharing activities, exchanging information, and their own experiences to find satisfactory solutions for all involved in the process [16,17]. The management planning meetings, based on the LPS, support and encourage the exchange of information and experiences among the stakeholders, contributing to a more collaborative and engaged work environment focused on meeting the group’s objectives.

7. Establish formal routines for analysis and feedback between the planning and control systems of the sectors. These routines should be well-defined, aligned with the needs of all stakeholders, and designed to facilitate the participation of everyone involved. Regular feedback sessions between sectors and structured communication channels can be implemented to ensure that the exchange of information and feedback is systematic, transparent, and beneficial for all parties involved.

8. Define clearly the individuals responsible for coordinating each subsystem, and the ones that should facilitate the integration. Indeed, while the planning approach is decentralized, having leadership roles within each sector (design, manufacturing plant, and construction site) and a designated coordinator for integrating the three planning and control systems is crucial. These leaders play a vital role in ensuring that the plans are effectively executed, coordinating the activities within their respective sectors, and fostering collaboration and alignment with the overall objectives. Additionally, it is important for all individuals involved to be committed to their tasks and responsibilities, understanding the significance of their contributions to the overall success of the integrated system.

5. Conclusions

This study presents the preliminary version of a planning and control model that integrates design, manufacturing, and site installation units in the context of modular construction. It also seeks to understand and identify the necessary interactions between those planning and control systems, in order to improve the management of complexity of this type of production system. The effective integration of production planning and control between design, factory, and construction is essential for the success of mass customization in modular construction. Some initial theoretical and practical contributions to the field of planning and control in the context of modular construction must be highlighted.

Among the theoretical contributions, this investigation proposes a decentralized and integrated
Production Planning and Control model, that facilitates alignment between different production units. Moreover, the proposed model enables a pull production based on the specific requirements of the projects, which need to be fulfilled within short lead times while delivering customized products. This model is strongly based on the Last Planner System, and also on Location-based planning and control, which can potentially improve the flow of information between the sectors, with more accurate, transparent, reliable, and up-to-date information regarding the system's status. Furthermore, it is able to foster a greater sense of collaboration within and between the sectors.

In practical terms, a set of proposed guidelines were defined, which represent prescriptive knowledge that can be used by modular construction companies. It is worth mentioning that this study was based on data from only two construction projects, although the company had several other simultaneous projects. Future research will explore the adaptation of the proposed model in multiple projects, and also the integration to other sectors, such as supply chain management and quality management.

Further activities in this research project will involve assessing the impacts of the changes introduced in the planning and control, for design, manufacturing and site installation. A set of new metrics have been defined for that assessment, including planning effectiveness, adherence to small batches, work-in-progress control, and synchronization between processes.

References


Sumaq Wasi, Analysis of the experience in bioclimatic social housing in Andean areas of southern Peru

Abstract: The rural territories of southern Peru above 3800 meters in the Andes mountain range are the highest inhabited places on the planet, with a very cold climate (reaching -15°C in winter), extreme solar radiation and high poverty rates. In 2020, the Peruvian government began a national rural housing program called “Sumaq Wasi” using two types of housing that would be built in those high areas to compensate for the lack of adequate bioclimatic and habitat requirements. One of these typologies was made of reinforced adobe (RA) and the other with confined masonry (CM). As case studies, two projects already built and inhabited in Puno (RA) and Arequipa (CM) have been analyzed using the MIVES method and the habitat concepts proposed by Joseph Maria Montaner to assess whether the objectives proposed by the project have been met in first instance. The rural housing program of the state has generated a great impact on the high Andean habitat, however, the present investigation has identified aspects to improve: How to adapt these modules to the climatic reality of each altitudinal floor of the Peruvian highlands, optimize isolation strategies thermal protection of roofs and walls, promote reinforced adobe modules in communities far removed from commercial centers for industrialized materials, also project mechanisms of reinforcement in the social dynamics that can modernize the traditions inherent to the artisan manufacturing process of adobe. To this we must add the possibility of improving the typological design to enable habitability and thermal comfort by users, respecting the criteria of spatial appropriation of each cultural fabric.

Keywords
adobe; bioclimatic architecture; habitat.
1. Introduction

In Peru, the climatic characteristics in high Andean areas have been weaving frameworks of unfavorable conditions for the inhabitants settled there, inhabitants who, due to cultural or economic conditions in many cases, do not consider their displacement. It is within this framework that Sumaq Wasi Project was born in 2019 as an effort by the Peruvian government to improve habitability conditions associated with extreme cold which during winter times can reach temperatures of -15°C in populations located above the 3800 masl.

Although the Project was executed with a scope that resolves adverse conditions (COVID 19 pandemic and the remoteness of some populated centers), after some years since its implementation, it is necessary to evaluate the characteristics of the project that would allow us to establish improvements to future projects of the same nature and in this critical exercise perhaps identify variables that were not taken into account at the time and that would help promote a more coherent response to the project, not only in construction areas but also in aspects of understanding of habitability as a more complex spectrum than the mere fact of occupying a space. Sumaq Wasi is the first large-scale rural housing project developed by the Peruvian state, in 2021 12,000 units were built [1] and for the period 2022-2024 the goal is 32,000 units [2].

1.1. Case Study

The development of this article focuses on the projects (case studies) built in Sibayo (Fig.1), located at Arapa (3838 m.s.n.m.) and San Juan de Tarucani (Fig. 2) (4210 m.s.n.m.) that, although they have similar climatic characteristics and geographical conditions, it was decided to develop a different construction system for each place, being the reinforced adobe (RA) and confined masonry respectively (CM). Understanding the construction process of the inhabited space as an ontologically cultural response (Rapoport, 2003), it is worth asking which of the two construction systems best contributes to its consolidation, as they respond to specific climatic requirements of the area and of habitability.

![Figure 1. Reinforced adobe module. Source: PNVR](image1)

![Figure 2. Confined masonry module. Source: PNVR](image2)

1.2. Constructive alternatives

Reinforced Adobe (RA): It is a system based on the use of cane, opened horizontally and whole vertically, anchored to the foundation and screed beam including courses of clay mortar [3].
Confined masonry (CM): Based on the use of reinforced concrete beams and columns that complete the entire perimeter of the construction. In this case, the walls are settled at first and then the concrete is poured [4].

2. Methodology

Based on the complexity of the research (quantitative and qualitative variables) is that the Integrated Value Model for a Sustainable Evaluation (MIVES) is coupled to the research methodology. This methodology allows us to systematize information in simple steps, relying on tools such as value functions and the weighting of variables by groups of experts, achieving a comprehensive approach in drawing final conclusions. A weighting is given to each one of the alternatives from a dimensionless magnitude called “Sustainability Index” (Fig. 4) based on a process of disaggregation of different evaluation parameters. The phases of the MIVES methodology are: a) Approach of the decision-making tree. b) Creation of value functions, c) Assignment of weights by a panel of experts. d) Evaluation of the alternatives: the value index is obtained for each one of the proposed alternatives [5].
2.1. Development of the Requirement Tree

It is achieved by integrating the most discriminatory and main aspects to be studied, grouping in the same way requirements, criteria and indicators of the evaluation model (economic, environmental and habitability). These 3 criteria respond to a sustainability evaluation and seek a holistic vision, a panel of experts has been consulted so that they can weigh the level of importance of each variable. The tree components and their structural correspondence are shown below:

![Diagram showing the requirement tree with weightings given by the specialized group.]

Figure 5. Tree of requirements with the weightings given by the specialized group. Own source.

2.2. Characterization of the techniques:

The formulation of the requirements tree will be based on the detailed analysis of each of the construction systems with which the modules in question are developed. The analysis will be given from the perspective of economic, environmental and habitability indicators, so later these indicators will be able to evaluate each of the modules from the spectrum of their construction systems.

2.2.1. Economic indicators:

The variable of cost per m² (C1) was considered, taking into account the useful habitable area, since the thickness of the adobe walls and confined masonry are very different. In addition, the time required by each technique (C2) was considered, for this the time necessary to build 10m² of wall was taken as a parameter, in this sense the confined masonry almost triples that of adobe since the formwork and concrete setting times are much greater.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Cost - C1 Manufacturing and assembly - I1</th>
<th>Time - C2 Execution-time - I2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Useful area (m²)</td>
<td>$/m²</td>
</tr>
<tr>
<td>Reinforced Adobe - AR</td>
<td>22.0</td>
<td>340.0 $</td>
</tr>
<tr>
<td>Confined Masonry - CM</td>
<td>23.0</td>
<td>413.0 $</td>
</tr>
</tbody>
</table>

Table 1. Assessment of Economic Indicators. Own source.
2.2.2. Environmental indicators:

To measure the thermal comfort (C3) the thermal conductivity parameter was used, since this value allows to establish the insulation capacity of the material, in this sense the adobe presents a better performance. The other criteria has been the emissions (C4), for this the Kg of CO2 emitted in the production of the material for 1m2 of wall was used, in this sense the confined masonry triples the emissions with respect to adobe because it requires more energy in the manufacture of calcined clay bricks.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Thermal comfort – C3</th>
<th>Emissions – C4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thermal conductivity – I3 (W/mk)</td>
<td>Carbon footprint – I4</td>
</tr>
<tr>
<td>Reinforced Adobe - AR</td>
<td>0.46 [8]</td>
<td>Reeds</td>
</tr>
</tbody>
</table>

Table 2. Assessment of Environmental Indicators. Own source.

2.2.3. Habitability indicators:

As Joseph Maria Montaner defines “Housing is the first space for socialization and the spatial representation of the various family groupings. For this reason, it must be capable of accommodate the diverse ways of living that are evident in 21st century societies”[11]. As it declares, considering the habitability indicators will allow us to approach a better fitting of the house to the users. Using the Maslow Pyramid scheme as a starting point, it is possible to build a relationship between the main needs that must be satisfied in the process of inhabiting [12]. This scheme allows us to consider variables that evaluate the capacity of the SUMAQ WASI Project to respond to habitability, a phenomenon given from the interaction of the user with the architectural fact. The Vital Functional and Flexibility variables are identified in order to manage variables that can be measurable or described without falling into arbitrary judgments. As for the first, this is described as a basic characteristic to guarantee the health and life of the user [13] [14]. Regarding flexibility, this is considered in terms of adaptability to the daily life conditions of the user as well as the possibilities of change in its architectural programmatic scheme [15].

<table>
<thead>
<tr>
<th>Technique</th>
<th>Flexibility – C5</th>
<th>Vital/functional – C6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coupling actions – I5 (% multipurpose area)</td>
<td>Service Areas – I6 (% Service Area)</td>
</tr>
<tr>
<td>Reinforced Adobe - AR</td>
<td>33%</td>
<td>0%</td>
</tr>
<tr>
<td>Confined Masonry - CM</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 3. Assessment of habitability indicators. Own source.
Habitability

Physiological Needs
Locating the bathroom outside of the module limits its use in high cold seasons.

Feeding
A cooking area is not contemplated, which means that this area is considered outside the home, limiting activity by separating it from the housing core. The low temperatures in the area are a limitation when making use of service areas outside the housing module.

The structural design of the house does not allow the removal of walls since they are all part of a collaborative integral structural response (load-bearing walls).

The initial module allows the integrations of the bedrooms to achieve a space with a larger area. This action occurs removing the drywall that separates them. This allows a multipurpose area of 12.17 m².

Flexibility

Coupling Actions
In this module, space coupling actions are not considered (all are integrated structural work walls). Figure 6.

Figure 6. On the left the reinforced adobe module and on the right the confined masonry module. Source PNVR

3. Results

The results shown in Table 4 come out of a unification and evaluation process through the MIVES software. This summary is the synthesis of the results of the Sustainability Index evaluated in each of the modules from the perspective of its construction system. In this table, the scores for each criterion, indicated and analyzed requirement have been broken down. These scores are:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Economy</th>
<th>Environment</th>
<th>Habitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion</td>
<td>C1</td>
<td>C2</td>
<td>C3</td>
</tr>
<tr>
<td>Indicator</td>
<td>I1</td>
<td>I2</td>
<td>I3</td>
</tr>
<tr>
<td>Reinforced Adobe - AR</td>
<td>0.080</td>
<td>0.128</td>
<td>0.207</td>
</tr>
<tr>
<td>Confined Masonry - CM</td>
<td>0.035</td>
<td>0.021</td>
<td>0.126</td>
</tr>
</tbody>
</table>

Table 4. Scoring of the indicators to obtain the Sustainability Index. Own source
The reinforced adobe (RA) shows a higher result with respect to the Sustainability Indices, achieving the value of 0.576 due to its low environmental impact as well as its lower cost in manufacturing and construction process while the masonry technique due to its high production costs and higher CO2 emission rates during its industrialized production process obtain a low value in the rates, being this 0.198. In a comparative view from the habitability perspective, the adobe modules consider the possibility of coupling, increasing the positive weighting in their favor.

![Figure 7. Assessment of the indicators - Sustainability Index. Own source](image)

**4. Discussion**

Economically, the score associated with construction costs in reinforced adobe is lower than masonry. Reinforced adobe techniques have the advantage of using local material, reducing the cost of production. Confined masonry when using industrialized materials must be purchased in the city, considering the transfer of material as an item that increases the final amount of work. Finally, the technique in reinforced adobe considers less execution time because it does not require formwork or setting periods at the same time that it does not require skilled labor as in the case of confined masonry.

About the environmental characteristics, reinforced adobe techniques have a lower carbon footprint thanks to their manufacturing process and better thermal performance against cold. Due to the industrial nature of its production, masonry requires greater energy consumption, which can be understood as higher CO2 emissions. The reinforced adobe technique as it uses local materials reduces emissions.
associated with transportation, the opposite with confined masonry that requires the transportation of materials from cities to rural communities. The thermal insulation of adobe constructions is superior to that of confined masonry due to its greater thermal inertia and wall sections. Considering the habitability values, both proposals do not fulfill minimum indices in terms of Vital-Functional considerations. The value of flexibility is considered only in one of the module proposals when it integrates two spaces. The flexibility value should be considered from the architectural program proposal, the same one that should start any discussion of housing projects. In the case of the SUMAQ WASI program, the architectural program is not addressed as an initial design tool, which leads to a single type of hard housing.

Flexibility in cases of housing typology in rural cultural contexts could and should be boarded from studies of cultural dynamics that make up the construction of housing (as Rapoport rightly indicates). Said this, construction should not only refer to the material fact of the house but also to the meaning of the material as an element of identity. From this perspective, the adobe typology (RA) contributes to the construction of identity and social networks in the areas in which it is projected.

The fact of not having service areas for kitchens would make the users improvise them within the typologies. This opens up the possibility of both health risks (combustion smoke concentration) and insufficient use of areas within the typologies (insertion of kitchen areas within the typologies without having space). In both cases, the need to take the architectural program as a starting point hand in hand with the social and cultural dynamics of the population is highlighted in order to define a design that fits the user. The relation between flexibility variables – structural possibility subject to change, have not been considered, hindering the changes that make it possible to adapt the original typology.

The sustainability index obtained for reinforced adobe (0.576) confirms that this construction technique would be more relevant to be replicated on a large scale in a complex territory such as the Andes mountain range at more than 3500 m.a.s.l. compared to the confined masonry that it obtains (0.198), this constructive alternative should not be ruled out for populated centers close to centers of sale of industrialized materials, with good road connectivity and availability of labor, otherwise the associated cost overruns difficult viability of the projects.

5. Conclusions

- Although this project was a government initiative, subsidizing the cost of the modules, by taking them to a self-management process of the project the costs in the case of confined masonry modules (CM) reduces their viability due to the high cost of materials, the industrial process involved, the relocation process and the lack of skilled labor. The fact of having a shorter work execution time in the case of reinforced adobe (RA) is directly related to the faster use of the modules, which can also be understood as a greater coverage of housing units per family in less time.

- The confined masonry modules (CM) require an industrial manufacturing process supported by high CO2 emissions, this without counting the emissions required for the entire process of transferring the material from the production areas to the required locations in Arapa and San John of Tarucani. Regarding thermal conductivity, reinforced adobe (RA) shows better response rates to low temperature conditions in the areas. If the cultural value of the material (RA) is added to this it would be pertinent to re-evaluate the massification of this construction process in order to contribute to the reduction of the carbon footprint as well as to the construction of the collective identity in the communities where it is carried out. the project.

- Both projects do not consider habitability conditions with respect to the service areas (any of
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Both projects do not consider habitability conditions with respect to the service areas (any of them has considered the construction of these areas) which hinders the proper interaction between users and the modules by having to supply these deficiencies in areas outside the module. The lack of functionality is aggravated by taking into account the low temperature conditions of the areas. On the other hand, flexibility is reflected only in the Adobe Reinforced (RA) module, at the same time that the possibility of coupling new spaces is not considered. Since housing is an extension of the user’s functions (having analyzed in this work those of a physiological order and adaptability of the space to future user requirements), the habitability character of both projects is possibly diminished by the lack of understanding of the dynamics of the user-module relationship.

- The favorable result towards adobe as the best material for the proposed typologies (understanding that said typologies are framed in a specific geographical / cultural context) calls attention to initiate research processes around the flexibility of said material in order to increase the possibility of the habitability response of said proposals. This would contribute both to the improvement of proposals already built and to the possibility of developing a subprogram to improve in parallel to the SUMAQ WASI project already underway. Said solutions must take into account the possibility of: Increasing the occupied area, diversifying uses in the proposed spaces, coupling spaces with each other and adapting to the progress of needs of each stage of the life of the inhabitants.

- Besides the good intentions that motivated the SUMAQ WASI program, after this analysis we can conclude that these modules could optimize both their design aspects and construction aspects. This could be done by focusing on a greater understanding of the user, both from their uniqueness as an individual in the community as well as considering the individual as part of an environment that requires holistic solutions in order to reduce the risks of the environmental decrease.

References


Author Contributions: Conceptualization, J.C. and M.M; methodology, J.C; validation, J.C and M.M.; formal analysis, J.C and M.M; investigation, J.C and M.M; resources, J.C and M.M; data curation, J.C and M.M ; writing—original draft preparation, J.C and M.M; writing—review and editing, J.C and M.M; visualization, J.C and M.M


8. C. Guigou, La tierra como material de construccion (Earth as a building material). Colegio Oficial de arquitectos de Canarias, España, 2002.


15. P. Fernandez, Hacia una vivienda abierta concebida como si el habitante importara, DISEÑO. España, 2015.

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Abstract: Vernacular constructions are the result of generationally inherited knowledge. These types of constructions took advantage of the resources of the environment and the knowledge of the territory to solve habitability and survival needs in rural contexts. In the research presented, two construction typologies are recorded and analyzed using digital photogrammetry (SFM): putucos (Peru) and cocons (Spain). The putucos are constructions made up of a single space that serve to shelter and are built with champa, material extracted directly from the ground. They have a quadrangular or rectangular floor, with four side walls that, through an inclination, configure the roof, through the approximation of rows of material or false dome. The cocons are constructions made up of a single interior space that serve to store rainwater and are built solely with stone. They have a circular floor, with side walls, an opening on the perimeter that allows access to the interior and covered by an approximation dome of courses with membrane behavior. The methodology applied in these two constructive typologies is based on a massive data recording technique through digital photogrammetry (SFM), to then be processed using the Agisoft Photoscan software, and finally the two-dimensional and three-dimensional data will be processed with the Rhinoceros 5 software. This methodology has made it possible to obtain three-dimensional models with millimeter precision and to make a comparison with each other; Although the uses and materials used for its construction are different, the geometry is very similar. The comparison of these has allowed us to show similarities and differences, both constructively, formally and structurally. These three-dimensional models also allow us to learn about this heritage, by definition sustainable and adapted to the environment. The dissemination of this vernacular heritage through augmented reality tools facilitates its access, prevents loss of value and increases knowledge about a more sustainable application of the material resources of the environment.

Keywords
Putucos; Cocons; Digital photogrammetry
1. Introduction

Vernacular architecture is becoming more important nowadays as constructions that represent social, cultural and patrimonial values of a specific area, so it is necessary a big amount of documentation to record that diversity [1]. Precise studies of this rural architecture are important for the development of serious policies to protect them [2]. Several recent investigations deal with the survey and recognition of the characteristics of vernacular constructions [3] by means of technologies that allow digital reconstruction [4], that allow to take better samples and understand their unique properties.

The investigation tests the possibilities of massive data capture techniques to survey and analyze vernacular constructions and formal properties. Two typologies of vernacular constructions are selected which present a similar form. These two typologies are built with a similar construction technique, despite being located in different parts of the world and using different materials Figure 1. In addition, both typologies answer to the needs of the population that inhabits them. It was identified that both architectures seek the approach to water: the putucos due to the need for access to fertile soil for agriculture and livestock, which causes to be located in areas with constant flooding; while the cocons allow water to be stored for domestic purposes, since they are located in an area with little rainfall.

The putucos are pre-inca constructions located in the andean highlands of the department of Puno, Peru. They are located on the shores of Arapa lake and the Ramis river, a highly floodable area. The inhabitants of this area settled in this place due to the fertility of the land, however they had to face challenges such as constant flooding and the cold and dry climate of the sector. That is why the putucos are a vernacular housing response that serves as a refuge.

These constructions are characterized by presenting a dome on their roof that arises from the reduction of the champa courses from a square or rectangular plan, as can be seen in Figure 1. The champa from quechua language, is a block of earth extracted directly from the ground, which is left to dry in the sun for a few days, then they are placed in such a way that the roots are exposed under the next line of champa. With this construction system, the putuco ensures its structural stability, due to the fact that the champa blocks are joined and form a unified structure, which ensures its stability against floods. It is important to mention that the putucos work well thermally [5], which is important since they have a sleeping/cooking/storage function, or a mix of two activities.[6].

The cocó is a water tank formed by a cavity responsible for storing rainwater and an upper part responsible for protecting this water from direct solar radiation and promoting ventilation. This type of construction is isolated and linked to a slope of the land that favors the catchment and entry of water into the interior, as can be seen in Figure 1. The cocó is covered by a dome between a system of approximation of rows and membrane behavior. There are single roof rows and others covered with little stones. The cocons arise from the need to have water for domestic consumption, for the hydration of people and animals and for hygiene. It is for this reason that the cocons are always next to a farmhouse, a shack or a shelter. The orientation of the opening of the cocó must prevent the entry of leaves and other plant elements that could damage the water, therefore, the opening is oriented against the direction of the prevailing winds [7].

The cavity responsible for storing the water can be dug directly into the rock or built and covered internally with mud and lime. In this way, an impermeable barrier is created and prevents the water stored inside from being lost. In order to conserve this water, direct sunlight must be avoided and ventilation must be encouraged through the entrance of the cocons and the separations that may be left between the different stones. The construction of the cocons was based on the economy of resources [8]. The location within the farm depended on the location of the rock ledge and that it could be accessible.
2. Materials and Methods

The methodology used is divided in three main phases: data collection, data processing, and interpretation of results. Five examples of each typology are surveyed, both the putucos and the cocos. The digital models obtained allowed to analyze dimensional and formal characteristics of both typologies.

The research is based on the surveying of vernacular constructions using digital photogrammetry based on Structure From Motion. It is a massive data capture technique which allows to obtain accurate three-dimensional models of an element, which incorporates its texture with photographic quality. Structure From Motion (SFM) is based on three-dimensional reconstruction algorithms that generate 3D objects through a semi-automatic process. There are different software solutions that can be performed without a very specialized knowledge by the user. That is why there are many examples of its application in various disciplines. Its use is recognized especially in archeology [9,10, 11].

This digital technique makes it possible to obtain drawings that reproduce the current state of the studied elements. This technique has generally been used as a conservation measure in the so-called "monumental" heritage that, despite often having the historical floor plan, has allowed the current state to be generated in an agile and effective way [12, 13].

However, since many of the surfaces are extremely irregular, this method provides a noisy point cloud. Methods should be applied to clean the data for further area or volume studies. Along these lines, studies have been carried out to standardize the point cloud along a building [14] and eliminate noise [15].

2.1. Putucos

2.1.1. Selection and description of putucos

- Putuco 1: Currently abandoned, and does not belong to an architectural complex.
- Putuco 2: Its function is to sleep and cook, it is made of champa and earth coating, it is over 30 years old. The complex is made up of a putuco and a sheep corral.
- Putuco 3: Putuco built in exposed champa, which is currently abandoned, has no surrounding buildings.
• Putuco 4: It is the only putuco built in adobe, it has earth coating on the outside. His function is to cook. It is over 45 years old. It forms part with four other adobe constructions that make up a central patio.
• Putuco 5: Its function is to cook, it is made of champa and earth coating. It is part of a set with four other adobe constructions forming a central patio.

2.1.2. Characteristics of photogrammetric models

Table 1 shows the characteristics of the putucos after performing the photogrammetry. It should be noted that the putucos that generated the most accurate data are putucos 2 and 4, since photographs of both the interior and exterior were allowed. In the case of putucos 1 and 5, photogrammetry could be carried out only on the outside, and in the case of putuco 3 photogrammetry was carried out on the inside. The reconstruction of these putucos was carried out following observable characteristics in situ and taking into account the measure results of putucos 2 and 4.

<table>
<thead>
<tr>
<th>Putuco</th>
<th>Number of photos</th>
<th>Link point cloud</th>
<th>Dense point cloud</th>
<th>Number of vertex (model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Putuco 1</td>
<td>71</td>
<td>70.558</td>
<td>2.590.554</td>
<td>13.660</td>
</tr>
<tr>
<td>Putuco 2</td>
<td>151</td>
<td>162.935</td>
<td>12.560.897</td>
<td>71.309</td>
</tr>
<tr>
<td>Putuco 3</td>
<td>92</td>
<td>108.489</td>
<td>11.890.041</td>
<td>53.352</td>
</tr>
<tr>
<td>Putuco 4</td>
<td>184</td>
<td>177.086</td>
<td>10.402.392</td>
<td>57.634</td>
</tr>
<tr>
<td>Putuco 5</td>
<td>47</td>
<td>55.201</td>
<td>4.850.606</td>
<td>22.545</td>
</tr>
</tbody>
</table>

Table 1. Putucos photogrammetry data.

2.2. Cocons

2.2.1. Selection and description of cocons

• Cocó 1: This cocó is without rivet with perimeter wall and horizontal plane, visible keystone and partial integral opening.
• Cocó 2: This cocó is without rivet with wall perimeter and horizontal plane, keystone no visible and partial integral opening.
• Cocó 3: This cocó is little stones, perimeter wall, keystone not visible and integral opening complete.
• Cocó 4: This cocó is without rivet with wall perimeter and horizontal plane, keystone no visible and partial integral opening.
• Cocó 5: This cocó is without rivet with wall perimeter and horizontal plane, keystone no visible and full integral opening.
2.2.2. Characteristics of photogrammetric models

Table 2 shows the characteristics of the cocons after performing the photogrammetry. The number of processed images has varied according to the characteristics: geometry and characteristics of its context. In all cases it has been possible to perform both exterior and interior photogrammetry. These complete models have made it possible to accurately represent their formal characteristics.

<table>
<thead>
<tr>
<th>Cocó</th>
<th>Images</th>
<th>Geometry</th>
<th>Geometry &amp; Characteristics</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>72</td>
<td>54.285</td>
<td>6.984.530</td>
<td>166.400</td>
</tr>
<tr>
<td>2</td>
<td>112</td>
<td>81.007</td>
<td>18.631.023</td>
<td>563.339</td>
</tr>
<tr>
<td>3</td>
<td>55</td>
<td>14.738</td>
<td>8.098.161</td>
<td>243.944</td>
</tr>
<tr>
<td>4</td>
<td>57</td>
<td>59.205</td>
<td>8.539.713</td>
<td>270.291</td>
</tr>
<tr>
<td>5</td>
<td>56</td>
<td>59.539</td>
<td>6.164.556</td>
<td>187.581</td>
</tr>
</tbody>
</table>

Table 2. Cocons photogrammetry data.

3. Results

To obtain the measurements of the putucos and the cocons, three sections obtained from the three-dimensional models have been used. A longitudinal section, a cross section and a horizontal section have been made Figure 2. These sections have made it possible to obtain a total of twelve characteristic data for each of the constructions Table 4, Table 5, Table 6, Table 7, Table 8, Table 9.

Figure 2. (a) Section data of putucos; (b) Section data of cocons
### 3.1. Measurement results

#### Longitudinal section

<table>
<thead>
<tr>
<th>Putuco</th>
<th>(a) Average wall thickness (m)</th>
<th>(b) Average dome thickness (m)</th>
<th>(c) Indoor width (m)</th>
<th>(d) Indoor height (m)</th>
<th>(e) Door height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.33</td>
<td>0.34</td>
<td>2.26</td>
<td>3.75</td>
<td>1.40</td>
</tr>
<tr>
<td>2</td>
<td>0.34</td>
<td>0.34</td>
<td>2.89</td>
<td>3.53</td>
<td>1.46</td>
</tr>
<tr>
<td>3</td>
<td>0.33</td>
<td>0.32</td>
<td>2.87</td>
<td>4.28</td>
<td>1.45</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>0.35</td>
<td>2.52</td>
<td>3.44</td>
<td>1.08</td>
</tr>
<tr>
<td>5</td>
<td>0.30</td>
<td>0.31</td>
<td>2.82</td>
<td>3.90</td>
<td>1.72</td>
</tr>
</tbody>
</table>

**Table 4. Measures of the putucos.**

#### Cross section

<table>
<thead>
<tr>
<th>Putuco</th>
<th>(f) Average wall thickness (m)</th>
<th>(g) Average dome thickness (m)</th>
<th>(h) Indoor width (m)</th>
<th>(i) Indoor height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.30</td>
<td>0.31</td>
<td>3.29</td>
<td>3.74</td>
</tr>
<tr>
<td>2</td>
<td>0.36</td>
<td>0.31</td>
<td>3.27</td>
<td>3.52</td>
</tr>
<tr>
<td>3</td>
<td>0.33</td>
<td>0.32</td>
<td>3.19</td>
<td>4.31</td>
</tr>
<tr>
<td>4</td>
<td>0.35</td>
<td>0.25</td>
<td>3.31</td>
<td>3.46</td>
</tr>
<tr>
<td>5</td>
<td>0.30</td>
<td>0.33</td>
<td>3.43</td>
<td>3.87</td>
</tr>
</tbody>
</table>

**Table 5. Measures of the putucos.**

#### Horizontal section

<table>
<thead>
<tr>
<th>Putuco</th>
<th>(j) Wall surface (m²)</th>
<th>(k) Indoor surface (m²)</th>
<th>(l) Door width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.59</td>
<td>7.88</td>
<td>0.46</td>
</tr>
<tr>
<td>2</td>
<td>4.30</td>
<td>8.81</td>
<td>0.52</td>
</tr>
<tr>
<td>3</td>
<td>3.66</td>
<td>8.82</td>
<td>0.45</td>
</tr>
<tr>
<td>4</td>
<td>3.97</td>
<td>8.34</td>
<td>0.48</td>
</tr>
<tr>
<td>5</td>
<td>3.70</td>
<td>9.04</td>
<td>0.60</td>
</tr>
</tbody>
</table>

**Table 6. Measures of the putucos.**

#### Longitudinal section

<table>
<thead>
<tr>
<th>Cocó</th>
<th>(a) Average wall thickness (m)</th>
<th>(b) Average dome thickness (m)</th>
<th>(c) Indoor width (m)</th>
<th>(d) Indoor height (m)</th>
<th>(e) Door height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.373</td>
<td>0.552</td>
<td>2.882</td>
<td>2.305</td>
<td>1.346</td>
</tr>
<tr>
<td>2</td>
<td>0.826</td>
<td>0.418</td>
<td>2.673</td>
<td>3.025</td>
<td>1.725</td>
</tr>
<tr>
<td>3</td>
<td>0.751</td>
<td>0.289</td>
<td>2.279</td>
<td>1.732</td>
<td>0.771</td>
</tr>
<tr>
<td>4</td>
<td>1.103</td>
<td>0.375</td>
<td>3.608</td>
<td>3.317</td>
<td>1.802</td>
</tr>
<tr>
<td>5</td>
<td>0.621</td>
<td>0.231</td>
<td>1.560</td>
<td>1.432</td>
<td>0.627</td>
</tr>
</tbody>
</table>

**Table 7. Measures of the putucos.**
### Table 8. Measures of the cocons.

<table>
<thead>
<tr>
<th>Cross section (cocons)</th>
<th>(f) Average wall thickness (m)</th>
<th>(g) Average dome thickness (m)</th>
<th>(h) Indoor width (m)</th>
<th>(i) Indoor height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cocó 1</td>
<td>0,686</td>
<td>0,268</td>
<td>2,669</td>
<td>1,896</td>
</tr>
<tr>
<td>Cocó 2</td>
<td>0,845</td>
<td>0,391</td>
<td>3,301</td>
<td>2,324</td>
</tr>
<tr>
<td>Cocó 3</td>
<td>0,647</td>
<td>0,327</td>
<td>2,683</td>
<td>1,364</td>
</tr>
<tr>
<td>Cocó 4</td>
<td>1,080</td>
<td>0,294</td>
<td>3,045</td>
<td>3,114</td>
</tr>
<tr>
<td>Cocó 5</td>
<td>0,685</td>
<td>0,218</td>
<td>1,568</td>
<td>1,369</td>
</tr>
</tbody>
</table>

### Table 9. Measures of the cocons.

<table>
<thead>
<tr>
<th>Horizontal section (cocons)</th>
<th>(j) Wall surface (m²)</th>
<th>(k) Indoor surface (m²)</th>
<th>(l) Door width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cocó 1</td>
<td>8,601</td>
<td>6,053</td>
<td>0,960</td>
</tr>
<tr>
<td>Cocó 2</td>
<td>10,372</td>
<td>7,626</td>
<td>1,038</td>
</tr>
<tr>
<td>Cocó 3</td>
<td>6,775</td>
<td>5,076</td>
<td>0,697</td>
</tr>
<tr>
<td>Cocó 4</td>
<td>11,910</td>
<td>6,592</td>
<td>1,084</td>
</tr>
<tr>
<td>Cocó 5</td>
<td>1,794</td>
<td>1,527</td>
<td>0,636</td>
</tr>
</tbody>
</table>

### 3.2. Data collection results

Table 10 shows the relationship between the number of model points of each putucos and cocons processed. It is observed that the number of points obtained in relation to the images is lower in the putucos than cocons.

<table>
<thead>
<tr>
<th>Putuco</th>
<th>Relationship between images and points</th>
<th>Cocó</th>
<th>Relationship between images and points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Putuco 1</td>
<td>36.486,68</td>
<td>Cocó 1</td>
<td>97.007,36</td>
</tr>
<tr>
<td>Putuco 2</td>
<td>83.184,75</td>
<td>Cocó 2</td>
<td>166.348,42</td>
</tr>
<tr>
<td>Putuco 3</td>
<td>129.239,58</td>
<td>Cocó 3</td>
<td>147.239,29</td>
</tr>
<tr>
<td>Putuco 4</td>
<td>56.534,74</td>
<td>Cocó 4</td>
<td>149.819,53</td>
</tr>
<tr>
<td>Putuco 5</td>
<td>103.204,38</td>
<td>Cocó 5</td>
<td>110.081,36</td>
</tr>
</tbody>
</table>

### Table 10. Putucos and cocons relation photogrammetry data.
Table 11 shows the averages of the measurements obtained between the putucos and cocons, in order to make a comparison between both typologies. It can be seen that the (c) indoor width is very similar between both constructions, as well as the (b, g) average dome thickness. However, the putucos have a (d, j) indoor height higher by more than one meter, also the (a, f) average wall thickness and therefore the (j) wall surface, vary a lot due to the different material.

<table>
<thead>
<tr>
<th>Measures</th>
<th>Putucos</th>
<th>Cocons</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Average wall thickness (m)</td>
<td>0,310</td>
<td>0,735</td>
</tr>
<tr>
<td>(b) Average dome thickness (m)</td>
<td>0,332</td>
<td>0,373</td>
</tr>
<tr>
<td>(c) Indoor width (m)</td>
<td>2,672</td>
<td>2,600</td>
</tr>
<tr>
<td>(d) Indoor height (m)</td>
<td>3,780</td>
<td>2,362</td>
</tr>
<tr>
<td>(e) Door height (m)</td>
<td>1,422</td>
<td>1,254</td>
</tr>
<tr>
<td>(f) Average wall thickness (m)</td>
<td>0,328</td>
<td>0,789</td>
</tr>
<tr>
<td>(g) Average dome thickness (m)</td>
<td>0,304</td>
<td>0,300</td>
</tr>
<tr>
<td>(h) Indoor width (m)</td>
<td>3,298</td>
<td>2,653</td>
</tr>
<tr>
<td>(i) Indoor height (m)</td>
<td>3,780</td>
<td>2,013</td>
</tr>
<tr>
<td>(j) Wall surface (m²)</td>
<td>3,844</td>
<td>7,890</td>
</tr>
<tr>
<td>(k) Indoor surface (m²)</td>
<td>6,816</td>
<td>5,375</td>
</tr>
<tr>
<td>(l) Door width (m)</td>
<td>0,502</td>
<td>0,883</td>
</tr>
</tbody>
</table>

Table 11. Measures of the putucos and cocons.

Table 12 shows the proportional relationship between the access openings to the interior habitable space, both of the putucos and of the cocons. Proportional relationships allow geometric comparison and see if there are repeating patterns.

<table>
<thead>
<tr>
<th>Putuco</th>
<th>Relation of proportionality (door)</th>
<th>Relation of proportionality (indoor)</th>
<th>Cocó</th>
<th>Relation of proportionality (door)</th>
<th>Relation of proportionality (indoor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Putuco 1</td>
<td>0,329</td>
<td>0,603</td>
<td>Cocó 1</td>
<td>0,713</td>
<td>1,250</td>
</tr>
<tr>
<td>Putuco 2</td>
<td>0,356</td>
<td>0,819</td>
<td>Cocó 2</td>
<td>0,602</td>
<td>0,884</td>
</tr>
<tr>
<td>Putuco 3</td>
<td>0,310</td>
<td>0,671</td>
<td>Cocó 3</td>
<td>0,904</td>
<td>1,316</td>
</tr>
<tr>
<td>Putuco 4</td>
<td>0,444</td>
<td>0,733</td>
<td>Cocó 4</td>
<td>0,602</td>
<td>1,088</td>
</tr>
<tr>
<td>Putuco 5</td>
<td>0,349</td>
<td>0,723</td>
<td>Cocó 5</td>
<td>1,014</td>
<td>1,089</td>
</tr>
</tbody>
</table>

Table 12. Putucos and cocons relationship data
4. Discussion and conclusions

Photogrammetry has allowed us to obtain an exhaustive record of these two construction typologies that are sustainable, understanding that they respond correctly to the environment, where they are located, and that they solve the needs related to agriculture and livestock. In addition, it was identified that both constructions are made in measures related to the human body.

4.1 Putuco - Cocó relationship

Although they are constructions located thousands of kilometers apart, both have a similar formality due to the construction process carried out by people intuitively, without any rules or previous technical knowledge.

The activity or use of the architecture has a great influence on the size of the spaces, although similarities have been found in the constructive principles between both constructions, the cocons are slightly smaller because the human being does not inhabit them constantly, unlike the putucos where they serve to shelter people (sleeping, eating, storing).

Both constructions have the purpose of relating daily life with the need for water. In the case of the cocons, it allows the storage of water in an area with a lack of running water, while in the case of the putucos, it allows settling in a flood zone, which is fundamental for the harvest and domestic economy.

4.2 Photogrammetry

The interior light conditions in both cocons and putucos influence the meshing process. The putucos have a much darker interior, which impedes the complete generation of the photogrammetric process, on the other hand the cocons, being more illuminated in their interior, favor the generation of the complete model.

Cocons generate many more points during the meshing process due to the irregularity of the surface, while the surface of the putucos is more regular and requires fewer points to correctly complete the three-dimensional model.

The present investigation gives evidence to understand different sustainable architectures. By means of a previous knowledge of the place that allows building taking advantage of the materials and resources of the environment, these acquired constructive knowledge serve to be able to realize a sustainable contemporary architecture.

In addition, future comparisons between vernacular architectures are sought in order to encourage new constructions that re-signify this knowledge and constructive principles.

Supplementary Materials: Annex: sections

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Bibliography


23 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).
Annex: sections
Thermal characterization of an interior space of colonial architecture in Arequipa, comparative analysis of thermal transmittance of ignimbrite (sillar) envelope and contemporary material (drywall)

Arequipa is characterized by the cyclical occurrence of earthquakes, which has conditioned the construction systems and the application of local materials to its architecture, as is the case of the colonial houses in the historic center that stand out for the use of ignimbrite (sillar) in the thermal envelope, currently the colonial architecture has been replaced by constructions of framed structures, where the enclosures are being carried out mainly by dry construction (drywall). The objective of the study is the thermal characterization of interior environments in an office in a colonial construction with ignimbrite fabric, in comparison with offices made with contemporary materials like drywall construction system. The applied methodology consists: (i) modeling the thickness of the thermal envelopes, (ii) taking surface temperature measurements with a thermographic camera and ambient temperature with sensors, (iii) modeling the evolution of thermal transmittance with measurements of heat and relative humidity; and (iv) development of the comparative analysis of thermal transmittance between the office environments studied. For the colonial construction office, during the rainy season, maximum indoor ambient temperature values of 22.041 °C were obtained and the maximum indoor relative humidity was 59.384 %; on the other hand, in the dry construction it was found that the maximum interior ambient temperature was 23.381 °C, and the maximum interior relative humidity was 57.22 %. The thermal characterization allowed the comparison of the thermal performance between interior environments with ignimbrite factories (sillar) and dry construction (drywall) in order to understand the thermal comfort of the users who inhabit the offices.

Keywords
Ignimbrite, dry construction, thermal characterization

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1. Introduction

The city of Arequipa is the second most important city in the Republic of Perú. It is characterized by its Historic Center, declared a World Heritage Site by UNESCO in 2000. The city rises at the foot of the Andes mountain range, bordering three volcanoes, the closest and most representative of which is El Misti (5,825 m.a.s.l.). This proximity to the volcanic mountain range, added to the subduction of tectonic plates along the Peruvian coast, has caused the city to be cyclically subjected to strong earthquakes, which has led to successive reconstructions of the buildings of the old town since its Spanish foundation in 1540 until the mid-twentieth century, a situation that has conditioned and characterized the evolution of the constructive processes of its historic buildings [1].

Its architecture is characterized by the use of white and pink ignimbrite stone (volcanic material known locally as ashlar) in robust walls, arches and vaults, resulting in a type of architecture that represents the integrated response of native labor with European construction techniques and stylistic characteristics.

The constructive evolution in the built heritage of Arequipa is reflected in the colonial architecture developed in the sixteenth, seventeenth and eighteenth centuries by Spanish builders in principle and product of miscegenation in its term, this condition of learning, interpretation and response makes the buildings of architecture "... almost vernacular, if it were not for the attention to the fashions that mark the periods of evolution of the mestizo style" [2].

Arequipa’s colonial architecture is a typical regional architecture, which is largely equivalent to saying authentic. Typical architecture obeys constant norms, natural, historical, vital and temporary conditions of the region. The courtyard is the organizing element. It is made up of articulated courtyard, transition spaces (chiflones) that can represent variation in their location. The courtyards have a defined geometric shape and their proportion depends on the dimensions of the lot. The construction system is based on the use of ignimbrite, used for the walls as well as for the interior vaults and existing rail roofs. The architecture is seismic, ignimbrite, with lime-clad roofs and caisson walls consisting of two faces of hewn ashlars filled with lime, boulder or rubble (.90 to 1.20 wide) [3].

The ignimbrite is the material used for the houses in the city of Arequipa. This material, of volcanic origin, is characterized by a thermal conductivity of 0.16 W/m°C, a specific heat of 463.75 J/Kg°C and a density of 1306.96 kg/m3. [4].

On the other hand, there are several studies that analyze the evolution of colonial architecture in Arequipa, from historical, spatial, stylistic and constructive perspectives. However, there are few studies that address the thermal behavior of its interior spaces, allowing the valuation of buildings with heritage value by monitoring and measuring thermal transmittance has become one of the main challenges faced by historic cities such as Arequipa, so we propose a thermal study that allows us to characterize the constructive section of the mansions of Arequipa in comparison with contemporary construction systems such as drywall.

1.1. Backgrounds

As Benavente mentions in "la arquitectura de la vivienda colonial de Arequipa " the mansions are the embodiment of the typology of patio coming from Spain which was formed based on three factors that allowed to realize a model of civil construction that despite the time and the constant earthquakes managed to maintain a unity in its expression, the factors are: geological factor with the presence of earthquakes and ignimbrite volcanic material, the climatological factor dryness, sunshine, winds and temperature, and constructive factor due to the absence of wood; it also mentions that the courtyards become elements of environmental regulation of the mansions, allowing solar gain, wind regulation, as well as the presence of vegetation in second courtyards and orchards, which together with the water channels generate a microclimate [3].

The factors that condition Arequipa’s colonial architecture determine its authenticity and mark its
characteristics, Zuñiga mentions that this architecture is "almost vernacular" alluding to its process of miscenegenation that was marked by a condition of "learning, interpretation and response" where European fashions and styles were attended to [2].

Burga indicates that the construction system with ignimbrite was used in large houses and popular vernacular housing, characterized by wide walls, narrow openings with railings, gargoyles in the form of canyons and friezes, the ignimbrite is a light material of thick and simple constitution. [5].

Regarding thermal studies we have the work of Luis Carlos Herrerra-Sosa, in his article “Evaluación del desempeño térmico del sillar (ignimbrita) de Arequipa, Perú”, in which he thermally characterizes the ignimbrite building material as the sillar soga as 0.78 W/m2 K the sillar canto as 1.49 W/m2 K [4]. Mention should also be made of the study by José Andrew Zúñiga entitled "Estabilidad térmica de un edificio centenario de sillar (ignimbrita) en clima desértico frío. Hospital Goyeneche", in which he thermally characterizes the Goyeneche hospital by taking temperature and relative humidity both indoors and outdoors with two different data collection over time. [6].

On the other hand, works have been developed whose purpose is the application of knowledge in contemporary architectural design, which focus on the thermal performance of vernacular and traditional buildings.

Martín, Mazarrón, and Cañas monitored two houses, one traditional and one contemporary, built with different materials in Navapalos, Spain. The objective was to analyze and compare the thermal behavior. The results of the field tests showed better conditions inside the traditional houses. [7].

Liu, Wang, Yoshino, and Liu, do something with the same approach in a study in Yaodong, China, on vernacular housing. They made measurements of the internal and external temperatures of the walls; thermal comfort theory was used to assess the indoor environment. [8].

Başaran in Turkey, conducts research on the vernacular house of Harran, characterized by having a dome roof. Inside and outside temperatures and relative humidity were measured, as well as surface temperatures. [9].

2. Materials and Methods

2.1. Study cases

The case studies correspond to offices in two buildings of the Universidad Católica San Pablo de Arequipa - Peru, both environments share the following qualities: (i) They are office environments in constant use. (ii) They are environments without ventilation or direct lighting. (iii) They do not have windows or doors to open spaces. (iv) Both environments have artificial lighting throughout their period of use. (v) The range of use of the environments is from 8:00 to 17:00 hours on average.

The first case study corresponding to the The Center for the Arts of the UCSP, the building is located in the historic center of the city of Arequipa, on Palacio Viejo street. the building that corresponds to the typology of the colonial courtyard house of Arequipa, the structure of the building is composed of ignimbrite (sillar) with walls with a system called "muro de cajón" characteristic of the colonial houses of Arequipa and flat roofs made up of rails, the interior spaces are distributed around two main yards, the entrance has with a “zaguán”, a traditional space within the structure of Arequipa’s colonial housing that connects the interior of the house with the exterior of the city.

The building has various environments such as exhibition halls (permanent and temporary), souvenir shop, a chapel, a computer room, offices, auditorium and service spaces. The building is frequently used for cultural events. As it is an adapted building, some of the frequently used rooms, such as offices, are left without natural lighting and ventilation. These rooms have artificial lighting throughout their period of use. These spaces do not use artificial air conditioning instruments such as air conditioning or heaters.
The second case study corresponds to the San Pablo Catholic University campus, located in the buffer area of the historic center of Arequipa, on Quinta Vivanco street, the building corresponds to the reuse of a building. The original building was designed for a hotel by the Cooper-Graña-Nicolini firm in the 1970s. Built at the end of that decade, the hotel never came into operation, however, becoming an abandoned place. After a long period in this situation, the San Pablo Catholic University acquired it in 2004 in order to recycle it as an educational facility, a project that was designed by the architect Marcello Berolatti de la Cuba. Since its change of use, the building has had several extensions and remodeling. The original building is the St. John H. Newman was designed for hotel uses and was later adapted to its current educational uses. The rest of the buildings of the university complex are later and their design has better habitable conditions.

Among the main uses of the Newman building are: classrooms, dining rooms, laboratories, office spaces and services. The construction system of the building corresponds to the reinforced concrete frame, and uses the drywall to organize and divide the various environments. Because the uses of the building are adapted, there are environments such as offices that are left without lighting or natural ventilation. These spaces do not use artificial air conditioning instruments such as air conditioning or heaters.
2.2. Modeling of thermal envelope thicknesses

The selected environments were surveyed in situ where the architectural qualities of the ignimbrite (sillar) and drywall envelopes are evident, as shown in Figure 3.

The ignimbrite office corresponds to the UCSP Center for the Arts and has walls with an average thickness of 0.65 m. The drywall office corresponds to the UCSP San John H. Newman building and has walls with an average thickness of 0.15 m.

The modeling of the thermal envelope of the selected offices consists of the identification of the layers that make up the enclosing walls that will later be measured to identify their thermal transmittance, as shown in Figure 4.

**Figure 3.** Floor plans of the measured office environments, (a) UCSP Arts Center Office and (b) UCSP St. John H. Newman Building Office. Own elaboration.

**Figure 4.** Modeling of the thermal envelope of: (a) Ignimbrite walls with a “Muro de cajón” construction system in offices of the UCSP Center for the Arts (b) Drywall walls in offices of the St. John H. Newman Building Office. Own elaboration.
2.3. Measurements of surface temperature with thermographic camera and ambient temperature with sensors

Surface temperature measurements of the selected office environments were taken with a FLIR 128x96 Compact Thermal Camera, model C3-X, series 9050149613. The measurements consisted of capturing thermal and digital images of both ashlar and drywall walls. The environmental temperature measurements were taken with ONSET Smart 8-meter Temperature and Humidity Sensors, series: 21538572, 21538576, and ONSET wired Data Logger, series: 21549014, the measurement consisted of mounting the equipment in non-visible areas of the selected office environments. Measurements were taken every 30 minutes between March 22 and 30, 2023.

2.4. Modeling the evolution of thermal transmittance with heat and relative humidity measurements.

For the thermal characterization of the constructive section, we must understand that these are composed of three layers, two outer layers of ignimbrite and an inner layer of construction residue, so it is proposed to use the calculation methods of Bienvenido-Huertas [10], that takes the theory of Albatici and Tonelli and Dall’O from the measurements taken of Temperature in order to make an energy assessment of the constructive section. [11,12].

3. Results

3.1. Comparative analysis of modeling of thermal envelope thicknesses

The ignimbrite wall is characterized by having five layers intertwined between them, the first is a lime coating that in many cases has been removed from both the exterior and the interior, the second layer is of ignimbrite facing of about 20 cm thick, the central layer is of gravel of varying quality of 15 cm thick to finish with a layer of ashlar facing of 20 cm thick and lime coating. The drywall wall is composed of three layers starting with a 1.5 cm layer of plasterboard, a central layer of metal structure with thermal insulation and a layer of plasterboard. Basically, the insulation is centered on the thickness of a material. The material components can be seen in Figure 2.
3.2. Comparative analysis of surface temperature measurements with a thermographic camera and ambient temperature with sensors.

The following results were obtained from the indoor air temperature and relative humidity measurements of both the office in the Arts Center building and office N220 in the Newman building, as shown in Table 1 and Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Arts Center</th>
<th>N220</th>
<th>Exterior</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>T. Int</td>
<td>HR</td>
<td>T. Int</td>
</tr>
<tr>
<td>Min.</td>
<td>31/03</td>
<td>22/03</td>
<td>27/03</td>
</tr>
<tr>
<td></td>
<td>7.30 h.</td>
<td>14.30 h.</td>
<td>5.30 h.</td>
</tr>
<tr>
<td></td>
<td>19.59°C</td>
<td>44.42%</td>
<td>20.85°C</td>
</tr>
<tr>
<td>Max.</td>
<td>30/03</td>
<td>30/03</td>
<td>28/03</td>
</tr>
<tr>
<td></td>
<td>12.00 h.</td>
<td>21.00 h.</td>
<td>17.00 h.</td>
</tr>
<tr>
<td></td>
<td>22.04°C</td>
<td>64.41%</td>
<td>23.38°C</td>
</tr>
</tbody>
</table>

Table 1. Temperature and Relative Humidity

Table 2. Indoor and outdoor air temperature and relative humidity record. Own elaboration.

3.2.1. Air temperature:

The outside temperature ranges from 13.59°C to 22.21°C, which is clearly related to the presence or absence of the sun. The temperature drops considerably during the night, and begins to increase around 9:00 a.m., with the presence of the sun; on the other hand, around 6:00 p.m. the temperature drops again. The highest temperature point is around 14.00 hr. In the interior spaces, we observed that the temperature of the office inside the ashlar house ranges from 19.90°C to 22.04°C. The drywall office N202 presents a slightly higher temperature, ranging from 20.85°C to 23.38°C.
3.2.2. Relative humidity:

The outdoor relative humidity recorded has been very variable, ranging from 32.82% to 79.35%, it is worth mentioning that the week of measurement had the presence of precipitation, characteristic of the summer months, with an increase in relative humidity during the early morning hours. In the interior spaces the relative humidity is more constant, we observe that in the ashlar office, the relative humidity ranges from 47.02% to 59.38%, on the other hand, in the office N202 these values range from 40.64% to 57.12%, obtaining that the drywall space presents a lower relative humidity.

3.2.3. Thermographic camera:

The photographs taken with the thermographic camera were taken in the spaces adjacent to the offices, either in the corridors or in the adjoining offices. Figure 3 shows the range of temperatures recorded in the walls and openings of the office of the ashlar building, mostly between 15 and 17°C surface temperature (Figure 3). On the other hand, while in the drywall office, the surface temperatures recorded ranged from 17 to 19°C, as shown in Figure 4.

3.3. Comparative modeling analysis of thermal transmittance evolution with heat and relative humidity measurements

The results indicate that the data obtained show a thermal transmittance for the vertical walls of between 4.92 and 5.39 W/m²°C for the ignimbrite wall, while for the drywall wall a thermal transmittance of 3.91 and 4.30 W/m²°C was obtained.

The study of the floor slabs or vaults shows that the thermal transmittance obtained for the ignimbrite
ceiling at their narrowest point is 4.67 to 5.12 W/m²°C, while for the drywall slabs we have a thermal transmittance of 1.89 to 2.10 W/m²°C. As shown in Table 3.

Table 3. Comparative calculation between thermal transmittance of ignimbrite and drywall

<table>
<thead>
<tr>
<th>VERTICAL WALLS</th>
<th>CEILING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IGNIMBRITE 22/03/2023 01:00:01</td>
</tr>
<tr>
<td>c (stefan boltzmann)</td>
<td>0.0000</td>
</tr>
<tr>
<td>c (covesa condens)</td>
<td>0.9500</td>
</tr>
<tr>
<td>U (Wind speed m/s)</td>
<td>0</td>
</tr>
<tr>
<td>T (Surface temperature, ext. in k)</td>
<td>292.8050</td>
</tr>
<tr>
<td>T (Environmental temperature int. in k)</td>
<td>292.8900</td>
</tr>
<tr>
<td>T (Environmental temperature ext. in k)</td>
<td>288.6060</td>
</tr>
<tr>
<td>Thermal transmittance (U Albaric)</td>
<td>4.9231</td>
</tr>
<tr>
<td>Thermal transmittance (U Dall)</td>
<td>5.3396</td>
</tr>
</tbody>
</table>

4. Discussion

It can be observed that the outdoor temperature is lower and much more variable than the indoor temperature, and the outdoor relative humidity is also higher outdoors. This allows us to observe that in both cases of study the construction materials are protected from the exterior climatic conditions.

Both buildings are in the permissible comfort range, being the range established in Givoni’s psychometric graph between 20 to 27°C with relative humidity ranges between 20% to 80%. Therefore, during the summer season both offices provide thermal comfort to their occupants. Likewise, the drywall office is slightly more comfortable than the ashlar office.

The results indicate that the data obtained show a thermal transmittance for the vertical walls of between 4.92 and 5.39 W/m²°C for the ashlar wall, while for the drywall wall a thermal transmittance of between 3.91 and 4.30 W/m²°C was obtained.

The study of the floor slabs or vaults shows that the thermal transmittance obtained in the ashlar vaults at their narrowest point is 4.67 to 5.12 W/m²°C while for the drywall slabs we have a thermal transmittance of 1.89 to 2.10 W/m²°C.

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Bibliography


Methodology for the social housing project in Brazil based on co-design, mass customization and economic viability

In Brazil, the social housing design has been elaborated from a predetermined profile of families, without popular participation in the design decisions. Conventional and standardized solutions are adopted, without considering the real needs and specificities of future users. Housing developments in general do not consider the strategies of environmental comfort, energy efficiency and sustainability. Based on this scenario and seeking sustainable solutions for social housing projects, this study aims to develop a methodology for proposing a design process that considers the community participation in the design decisions, in addition to being sustainable and economically viable. Thus, the inductive method was used in a case study developed at Paulo VI Housing, in Belo Horizonte city, Brazil, which is among the 10 most vulnerable areas to climate change in the city. The methodology used the approaches of collective design and mass customization in two workshops with the community, where physical scale mockups were used. The residents assembled mockups with the layout of a house for their families, within the parameters of the Brazilian Social Housing System and later, chose finishing materials for their designed house. Structured questionnaires were also used to gather information about the community. Parametric simulation generated the housing units and building volumes. A financial viability study was carried out, comparing the value of a standard house unit with the value of a house project developed with community participation, within the maximum funding period allowed. The results indicate that users want spaces to work at home, to raise animals and plant food, as well as space to expand the house unit. In comparison with the standard house project, the cost of the new proposal brings an insignificant increase in the monthly installment of users.

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Keywords
Social Housing Project; Co-design; Mass Customization
1. Introduction

According to data from the Ministry of Regional Development (MRD) and João Pinheiro Foundation (FJP), the Brazilian housing deficit, in the base year of 2019, was 5.8 million houses. The study works with the concept of housing deficit as a stock of non-existent or inadequate housing. This housing deficit study comprises the excessive rent burden (42.3%), family cohabitation (41.3%), precarious housing (12.40%) and excessive density (3.90%). It is possible that families included in the excessive burden component with rent and makeshift homes are opting for more expensive rents due to lower transport cost for displacement. Still analyzing the study by MRD and FJP [1], it seems that the distribution of the total deficit by the income range is concentrated on 1 to 3 minimum wages (US$220 to US$660), which together with an income of less than 1 minimum wage account for 91.7% of the total deficit. According to the Ministry of Cities (MC) and the Fluminense Federal University (UFF) there is a trend towards an increase in the deficit. Brazil still needs to build approximately 30 million house units to meet the deficit plus vegetative demand [2]. Therefore, prioritizing public programs and policies aimed at remedying the mismatch between the housing deficit and the provision of adequate housing in the lower income brackets becomes essential. Several federal government programs have been trying to meet this demand for Social Housing (SH) over the years. It is worth remembering the "Minha Casa Minha Vida" Program (PMCMV) and the "Casa Verde e Amarela" Program (PCVA), which had the objective of creating mechanisms to encourage the production and acquisition of new house units (UH) by low-income families. The two programs, managed by the public bank Caixa Econômica Federal (CEF), have had as executing agents mainly the private civil construction companies [3-4].

The Brazilian socioeconomic background supports a quantitative model of housing production, numerically expressed as a housing deficit, which is always accompanied by a prospect of solution, over the years. This SH production based only on numbers has transformed housing provision into a problem, since it disregards the performance and environmental quality of the UH. It is also noticed:

a) Negligence in urban development solutions, since the settlements take place in the city’s outskirts, without access to urban services (health, education, transport and leisure).

b) Adoption of conventional and standardized design solutions, with minimum internal spaces, without considering the real needs and specificities of future users.

c) Predetermination of the families profile with absence of popular participation in design and construction decisions. Few models are proposed for all kinds of families, which, despite their diversity, are considered homogeneous just because of the low income.

d) Adoption of market practices aimed at profiting the civil construction industry and earning political capital by delivering housing to as many people as possible, to the detriment of the social function of the city and the functional and dimensional quality of the house project.

e) Both vertical multifamily and detached units housing developments do not consider the principles of environmental comfort, energy efficiency and sustainability. Most of the PMCMV projects have proved to not have good energy and/or comfort performance.
The SH design process is linear, sequential and with disconnected steps and has been shown to be inadequate.

Faced with the problem presented, the objective of this study is to point out a new path, developing an interdisciplinary approach methodology, based on simultaneous engineering, capable of proposing a new design process for SH that integrates actions, techniques, and procedures, which considers the users’ needs, incorporating high energy performance and that is economically viable.

The relevance lies in the development of a methodology, which can be used by architects, administrators or urban managers and will present an opportunity to deal with the SH design process in an interdisciplinary and integrated way, more suitable for users, more sustainable and feasible.

2. Materials and Methods

The study presented here is applied, interdisciplinary and based on the inductive method in addition to being qualitative and quantitative.

2.1. The study case

A case study was developed in the area of Paulo VI Housing, located in the city of Belo Horizonte, state of Minas Gerais, Brazil. This area is among the 10 most vulnerable areas to climate change, being identified as highly vulnerable to heat waves and dengue fever [5]. The population is about 3,736 people and 849 households (Figures 1 and 2). The population is mostly within the income range of 1 to 2 minimum wages.

2.2. Community participation and Presets

In architecture, the individual needs and preferences of end users ought to be addressed to ensure a successful project. Standardized SH have been a source of dissatisfaction for residents for a long time.

Community participation normally involves two approaches: the co-design one, capable of uniting multiple knowledge, is considered an effective tool to help residents plan their homes and make choices in the customization phase. Mass customization (CM), the subsequent approach, is a business strategy [6] that allows the end user to make choices within a limited range of product options [7], based on the needs of these users, with costs similar to those achieved in mass-production, but in a flexible process, which takes place before the product is delivered [8].

Another interesting point when seeking popular participation are works that use three-dimensional physical models or mockups. The use of mockups can improve the communication process between...
users and the designers, identifying subjective demands and priorities of users, elucidating the intentions of the project, especially for users or those who have decision-making power over the construction venture. Imai and Fabricio [9] developed a proposal for a three-dimensional simulation mockup, which was applied to a group of users, following a script of questions to be addressed during the procedure.

In this study, the simulation with the physical model was carried out based on SH models with approximately 50m², produced on a 1/20 scale. Models of furniture, walls and frames were offered to the users. Users thus made their choices to freely customize their houses.

A workshop was set up with the community of Paulo VI Housing and some methodological procedures were defined:

a) Direct observation technique: walkthrough. The objective was to know the area and create partnerships with the community residents, inviting them to the workshop.

b) Indirect observation technique: applying a form for surveying data on the composition and habits of the families. The objective was to collect data about the family composition, income and habits, and separate the participants into similar groups for the co-design process.

c) Co-design and mass customization techniques: method of analysis with the construction of physical models, described below.

d) Quantitative analysis of data and qualitative results.

2.3. Method of analysis with construction of physical models

This survey worked in the range of 1 to 3 minimum wages (US$220 to US$660), since the largest portion of the SH users is within this income range. Based on data from the Brazilian Program for Habitat Quality and Productivity (PBQPH/SiNAT; NBR-15575 [10]), some construction systems were selected for feasibility analysis of SH constructions (up to 4 floors).

The board for the house co-design had approximately 50 m², nearly the standard PMCMV unit area for families within the studied income range. At the same time, furniture within the standard minimum specifications of the PMCMV (FAR/FDS) was printed on a 3D printer. In addition, the cards of the “Game of spaces” were made with the names of the different rooms in a dwelling.

3. Results

3.1. The production of the pieces for the workshop

The pieces for assembling the mockups during the workshop were produced in scale 1/20, using 3D printers and laser cutter. A 6 mm, MDF board was used to make the base and smooth wall panels with different gaps. The following were produced: six 7.20 x 7.20 m base units in MDF wood panel with the 60 x 60 cm module engraved on the base, 12 sets of walls in modules of 60, 120, 240 and 300 cm, with several variations and 6 sets of varied furniture for the different spaces of the house (Figure 3), always with the minimum measures established by the government financing system.
3.2. The Game of Space

Some rectangular cards were produced on MDF board, inside the 60 cm module, where the name of the room could be read.

3.3. The Form

The printed form was applied at the start of the workshop. The participants answered and drew on the sheets of paper and later, the answers were tabulated (Figure 4). The analysis was qualitative.

![Figure 4. Main form results](image)

3.4. The Workshop

After an initial talking and in view of the answers to the form, the participants were separated into groups. Initially, the group was asked to set up the “Game of Spaces”. The objective was an exercise where the participants could make proximity relationships of the desired spaces. Later, the participants were invited to assemble the mockup, having as a reference the “Game of spaces” and using the limiting base of the project area, the panels and the furniture (Figures 5 and 6).
The technical team accompanied the entire workshop process but did not interfere in the group’s decisions. The main technical results observed indicate that in 65% of the houses drawings about where they live there was a roof, a symbol of warmth; in all 6 projects the areas for work inside the house and the “backyard” area are present; they refer to the uncovered area for raising animals and planting vegetable gardens. The notion of privacy was found to be of little importance, doors have direct contact with the bedrooms and kitchens. Many places had two windows in the same room, which suggests that natural ventilation is important.

3.5. Comparison between the cost of standard housing and housing designed with the Co-design and Mass Customization application process

In Brazil, the cost of construction is normally calculated using tables prepared by the regional civil construction unions. For the state of Minas Gerais, where the study case area is located, the values are established in Table 1. Thus, the cost of a standard dwelling would be approximately US$15,400.

### Table 1. Values from CUB (Basic Unit Construction Costs) in Minas Gerais State - June 2023

<table>
<thead>
<tr>
<th>Project - residential, low standard</th>
<th>Costs (US$/m²) (^1)</th>
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<tbody>
<tr>
<td>Social Interest Project (PIS): multi-family building up to 4 floors (2 bedrooms, 1 living room, 1 bathroom, 1 kitchen and service area)</td>
<td>308.5</td>
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</tbody>
</table>


A simplified cost calculation for adding the co-design process and MC was raised by the researchers. The value includes: the production of the mockup pieces in a 3D laboratory; printed promotional posters and flyers; design material; technical team salaries and transport; and coffee breaks for the workshop participants (about 50 to 100 people). This cost was about US$1,500. Table 2 shows this value within 30 years of the SH program financing. The monthly installment of the house unit would be increased to approximately US$4 a month, which seems to be feasible.

### Table 2. Comparison between the cost of standard housing and housing elaborated with the Co-design and Mass Customization application process.

<table>
<thead>
<tr>
<th>Standard unit cost (US$)</th>
<th>Adding co-design+MC process (US$)</th>
<th>Cost difference in 360 months of financing (US$/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15,400</td>
<td>16,900</td>
<td>4.2</td>
</tr>
</tbody>
</table>
4. Discussion and final remarks

The general objective of this article was to address the SH design in a case study considering the community participation in the design process. The study involved CM and co-design techniques, such as the use of physical models as a tool to understand the expectations and real needs of future users and indicate guidelines for application to SH projects in a community.

It is considered that the proposed methodology allowed community residents to make correlations between the space currently experienced, that is their home, and the project to be developed. For co-designing with communities, the physical models had characteristics that allowed their use as a didactic tool for communication between designers and lay users, making them a useful tool for encouraging participation. The mockups made it possible for the users to understand the importance of the openings position (doors and windows) and the arrangement of the furniture when organizing the layout. It was found that a house is no longer just a dwelling, but also incorporates the function of a work area. The uncovered or open areas are also areas of raising animals or vegetable gardens.

About the mass customization of SH, the importance of modulation of the constructive components became clear from the moment that changes in the assembly of environments and layouts are allowed within a pre-established base and module.

Regarding financial viability, it should be noted that the final proposal would still include some components of sustainable strategies. In this qualitative analysis, it is understood that as the built area does not change, the cost of the real state development would not change either. The increase in the installment to be paid by the user in the maximum financing period would be offset by energy and water savings. Still about financial viability, this design process takes longer, but according to Keeler and Burke [11], if the integrated and sustainable design establishes a longer duration in the initial stages, the final stages happen more quickly.

The close relationship between architecture and sustainability with regard to SH planning will only occur when the real estate market realizes that the quality of projects and customer satisfaction, which does not imply a substantial change in the cost of housing, is a technically viable and profitable business model, where the quality and dignity of social housing are not treated as an utopia, but as a way to achieve results for the good of the population and economic activity. At this point, the academy plays an important role in the searching for solutions that arouse the financial interest of the market and objectively promote the quality of life in low-income housing projects.

References


5. PBH (Prefeitura Municipal de Belo Horizonte). Análise de Vulnerabilidade às Mudanças Climáticas
do Município de Belo Horizonte. PBH: Belo Horizonte, Brazil, 2016.


A Simulation-based Sensitivity Analysis for Thermal Performance of Building Envelope Design Strategies Applied to a Social Housing Prototype in Victoria, Australia

Abstract: Poor building thermal performance and energy efficiency are common issues for social housing being occupied by vulnerable families and they tend to be considered as barriers to maintain their affordability and health and well-being. Furthermore, due to the limited budget for social housing development, it is much needed to enhance the building performance through implementing appropriate envelope design strategies effective to alleviation of these barriers. This research aims to identify and measure the present building envelope design conditions of a selected low-cost housing unit constructed in the State of Victoria, Australia, through the performance observation and simulation. Sensitivity Analysis is a method applicable to identifying the influential building envelope design parameters concerning thermal performance by calculating and analyzing the performance of applied design strategies in window, exterior wall, floor, and roof components. The design strategies are specified based on the systematic literature review, and the plug-in software tools such as Ladybug and Honeybee are utilized to measure the performance of each design parameter identified. The applied design parameters with related strategies including the window-to-wall ratio, solar heat gain coefficients, and thermal conductivity of building envelope materials. Through the quantification of these low-cost envelope design strategies and impacts can help architectural designers to improve the performance of social housing with due consideration of the users’ affordability of operational energy costs as well as health and wellbeing. The result of this research provides the energy performance of the implemented prototype model of 1520 Kw/h for cooling load and 1130 Kw/h for heating load, 87% of thermal comfort hours by the temperature set-point range between 19-24°C, and over 0.8 SRRC index impacts for Window to wall ratio in building envelope design by SA. The proposed envelope includes a WWR range 0.25-0.35, a north and west window SHGC around 0.35-0.5, and the related window U-Value does not exceed 0.75.

Keywords
Social Housing; Sustainability; Building Thermal Performance; Sensitivity Analysis; Design Parameters

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1. Introduction

Social housing has been seen as one of the crucial spaces impacting the living quality for vulnerable people, so as to maintain a harmonious social atmosphere. However, the development of social housing still suffers investment limitations because of its short-term lack of recharging, despite being a channel for investment that is conducive to booming development in the long run [1]. The severe initial budget exacerbates the poor thermal performance of social housing that the occupants’ comforts and well-being have not been adequately remedied for a long time. Based on the NatHERS, a national energy efficiency evaluation criterion for buildings in Australia, has defined the level of energy efficiency thresholds from one to ten. The social housing sector’s average quality can only meet a 5.5 rating as the minimum requirement for new building construction should be met by at least 7-rating in 2023 [2]. Moreover, the improvement of social housing building energy performance means an extra construction cost investment is needed, along with the 12% rose in construction fees compared to 2020 [3]. The limited budget for social housing faces the challenges of becoming more constrained [3, 4]. To improve the cost-effectiveness when delivering energy-efficient and thermal comfort social housing for occupants in need, a detailed design parametric framework is necessary to propose, optimizing the building energy and thermal performance by integrating the building components into the related design strategies [5]. Different from usually complicated houses, social housing is seeking the basic living demands of vulnerable people by implementing low-cost design strategies and maintaining simple functional spaces [6]. However, the current housing construction regulations in Australia do not address the detailed specifications of social housing’s unique attributes and needs. Instead, general building regulations meeting generic building energy standards make social housing fall into a state where building performance does not match its capital investment efficiently. Therefore, as a social housing designer, it is imperative to investigate the effect of building envelope parametrically by measuring the impacts of design factors in wall, roof, window and floor on energy efficiency and thermal comfort performance to form a systematic framework to support the optimization of social housing design in the policy making level.

Previous research shows the importance of passive building strategies to achieve a more energy efficient and thermal comfort indoor performance such as the insulation layer of building envelope, the building orientation, the size and material of windows on each side, and working efficiency with HAVC systems. However, social housing as a specific type of residential has unique space characteristics and requirements. Generally, social housing remains a micro-volume serve for a single occupant to reduce budget, including a single bedroom, a living room with an open kitchen area, and a bathroom [6, 7]. Therefore, the building parametric codes suit for social housing design strategies to improve indoor thermal comfort and energy efficiency still need to be figured out. This research is to propose a parametric design solution for social housing building envelope design to improve building thermal performance by identifying the influential parametric design factor with related design strategies using a systematic building modeling and simulation method.

2. Materials and Methods

In order to investigate the parametric design solutions for social housing thermal performance optimization, identifying the effect of related design parameters in the building envelope has shown its necessity. Sensitivity Analysis (SA), as a method to measure the impact of design variables on building performance can be verified by utilizing a series of steps in building modeling, building simulations, and quantitative data analysis [8, 9]. In detail, the research framework with applied methods and tools for investigating the SA of design variables in the social housing building envelope was shown in Figure 1. At first, a three-dimensional building model was built by using Rhinoceros to transfer the social housing prototype model information into a parametric model. Then, connect the Grasshopper
platform with the built 3D model by inputting the parametric information to the simulation plug-in software Ladybug and Honeybee for further parametric simulation. Ladybug and Honeybee have been used in many design projects for viewing applied solution outcomes and design optimization approaches by providing a simulation data collection channel [10]. The simulation process includes different parametric design variables settings, local weather file input, thermal comfort hourly data, and energy performance simulation. At last, the energy simulation output was collected and organized in Excel for further analysis, and the thermal comfort results were shown as a series of Psychrometric charts to demonstrate the annual thermal comfort hours. Based on the difference in simulation outputs, the impacts of each design variable could be measured and viewed to identify the impact evaluated by Standardized Rank Regression Coefficient (SRRC) indicators. The sensitivity of SRRC as an index was cited to express the ranking of impact with input design parametric variables. The SRRC index can be defined as positive or negative correlations depending on the impact of the current increment on the overall performance [11]. Therefore, it still can help identify the impact rank in numerical value whether the index of design variables improved or decreased the total building performance.

In addition, the social housing prototype was designed as a single-bedroom micro home with 29.67 square meters, and the plan drawing was shown in Figure 2(a). The test location was in Geelong, the temperate climate zone in the south side of Australia. The temperature range is between 5.7 to 35.8 degrees Celsius with dry summer and wet winter conditions. Australia has the largest amount of solar radiation in the world, which means that overheating caused by solar radiation has become the biggest challenge faced by local buildings. Furthermore, the issue of temperature fluctuations caused by climate change deteriorates the thermal performance as another housing crisis especially for the social housing sector. The quality control and risk assessment necessities its value for social housing construction from the early design stage. Based on the literature review, the window condition and wall insulation are the most important factors that impact the thermal performance of a residential building [12, 13]. This research selected window material U-Value, Window Solar Heat Gain Coefficient (SHGC), and Wall Insulation Thickness as design variables for SA. Furthermore, the thermal comfort criteria ASHRAE Standard-55 Version-2017 will be applied as an adaptive comfort model in this research to help simulate the annual comfort hours shown by the psychrometric chart [14]. Figure 2(b) explained the original thermal comfort hourly data under local temperature and relative humidity conditions. The comfort hourly data was set as a fixed value and kept energy consumption as a variable to measure the overall impact of each change of design variable input.

![Figure 1. The research framework for the applied methods of building simulation and Sensitivity Analysis.](image-url)
3. Results

3.1. Building performance of the prototype model

The initial energy performance and thermal comfort hour simulation results of the prototype model have been carried out. Based on the monthly total cooling and heating energy consumption shown in Figure 3(a), the amount of cooling energy used is more than the heating energy used in one year. The highest cooling load in July and August can reach more than 300 kw/h, and the maximum heating load is less than 250 kw/h even in the highest months of December and January. The total annual cooling energy consumption is 1520 kw/h while the heating energy consumption is 1130 kw/h.

As for the evaluated thermal comfort hourly data, this research is using ASHRAE Standard-55 2017, the human metabolism was set as default 0.6, and the Clo index was separate in summer and winter with 0.5 and 1.0. Figure 3(b) depicted that more than 87% of hourly Scatter plots are situated in the Comfort Zone when the HVAC temperature set-point range is between 19-24°C. The comfort hourly data has been reduced by the outside working and activity hours based on the occupant behavior schedule to achieve an accurate simulation result. The possible reason for the 13% discomfort hourly data may be because of the setback temperature during the nighttime. The air leakage triggered the fluctuation of inner relative humidity caused by wind could be seen as another error.
3.2. Sensitivity Analysis

According to the National Construction Code (NCC), the preliminary parametric settings for each design variable will be controlled in a legal range shown in Table 1. The active and negative SRRC of each input design parameters to the related outputs were shown in Figure 4. Based on the result of SRRC for each design variable in heating and cooling load, it clearly depicted the most sensitive design variables in building envelope performance is the Window-to-Wall Ration (WWR). Then, window SHGC also plays an important role in control building thermal performance. In addition, window material U-Value and thermal insulation thickness impacted the north and west side of the building more than the south and east area.

<table>
<thead>
<tr>
<th>No (DV)</th>
<th>Parameter</th>
<th>Unit</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>DV1</td>
<td>E-Wall Insulation-thickness</td>
<td>mm</td>
<td>75-150</td>
</tr>
<tr>
<td>DV2</td>
<td>W-Wall Insulation-thickness</td>
<td>mm</td>
<td>75-150</td>
</tr>
<tr>
<td>DV3</td>
<td>S-Wall Insulation-thickness</td>
<td>mm</td>
<td>75-150</td>
</tr>
<tr>
<td>DV4</td>
<td>N-Wall Insulation-thickness</td>
<td>mm</td>
<td>75-150</td>
</tr>
<tr>
<td>DV5</td>
<td>E-Glazing U-V</td>
<td>W m⁻²k⁻¹</td>
<td>2.5-7.5</td>
</tr>
<tr>
<td>DV6</td>
<td>W-Glazing U-V</td>
<td>W m⁻²k⁻¹</td>
<td>2.5-7.5</td>
</tr>
<tr>
<td>DV7</td>
<td>S-Glazing U-V</td>
<td>W m⁻²k⁻¹</td>
<td>2.5-7.5</td>
</tr>
<tr>
<td>DV8</td>
<td>N-Glazing U-V</td>
<td>W m⁻²k⁻¹</td>
<td>2.5-7.5</td>
</tr>
<tr>
<td>DV9</td>
<td>E-Glazing SHGC</td>
<td>-</td>
<td>0.36-0.68</td>
</tr>
<tr>
<td>DV10</td>
<td>W-Glazing SHGC</td>
<td>-</td>
<td>0.36-0.68</td>
</tr>
<tr>
<td>DV11</td>
<td>S-Glazing SHGC</td>
<td>-</td>
<td>0.36-0.68</td>
</tr>
<tr>
<td>DV12</td>
<td>N-Glazing SHGC</td>
<td>-</td>
<td>0.36-0.68</td>
</tr>
<tr>
<td>DV13</td>
<td>N-W to W-Ratio</td>
<td>%</td>
<td>20%-45%</td>
</tr>
<tr>
<td>DV14</td>
<td>N-W to W-Ratio</td>
<td>%</td>
<td>20%-45%</td>
</tr>
<tr>
<td>DV15</td>
<td>N-W to W-Ratio</td>
<td>%</td>
<td>20%-45%</td>
</tr>
<tr>
<td>DV16</td>
<td>N-W to W-Ratio</td>
<td>%</td>
<td>20%-45%</td>
</tr>
</tbody>
</table>

Figure 4. The SRRCs result of Sensitivity Analysis. The detail information will be listed as follows:
(a) the Annual Heating load SRRC Sensitivity Analysis result shown in the first panel;
(b) the Annual Cooling load SRRC Sensitivity Analysis result shown in the second panel.
4. Discussion

This paper aims to investigate the SA of building envelope design variables for specific prototypes of social housing to support the future design in achieving a more energy-efficient and thermal comfort social housing project in Victoria, Australia. The findings of this paper have shown that the energy performance of the implemented prototype model of 1520 Kw/h for cooling load and 1130 Kw/h for heating load; 87% of thermal comfort hours by the temperature set-point range between 19-24°C, and over 0.8 SRRC index impacts for Window to wall ratio in building envelope design by SA. Furthermore, the highest rank of design variables in both heating and cooling loads is WWR, and the second impactor is window SHGC. Compared to the previous variables, the proportion of window material U-Value and insulation thickness is relatively small. Therefore, the proposed envelope includes a WWR range of 0.25-0.35, a north and west window SHGC around 0.35-0.5, and the related window U-Value does not exceed 0.75.

5. Conclusion

This paper was limited to investigating more design variables to get a detailed design framework. It is expected that more comprehensive design variables with an extensive parametric range could be analyzed and further investigated in future work. In addition, the sensitivity analysis for social housing design parameter settings is based on the temperate climate conditions in the state of Victoria. A wider range of parameters is expected to analyze and to further simulate other climate conditions and make the comparison with different climate zones in Australia to attain a more comprehensive social housing design framework for the mass customization of energy-efficient and thermal comfort social housing in the new era.

Autor Contributions: Conceptualization, Wei, J. and Noguchi, M.; Methodology, Wei, J. and Wei, F.; software, Wei, J. and Wei, F.; validation, Noguchi, M., Sadick,A and Li, H.; formal analysis, Wei, J.; investigation, Wei, J.; resources, Wei, J.; data curation, Wei, J.; writing—original draft preparation, Wei, J. and Noguchi.; writing—review and editing, Sadick,A.; Li, H.; visualization, Wei, J.; supervision, Li, H.; project administration, Li, H.; funding acquisition, No funding.

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References


6. Wei, J.; Li, H.; Noguchi, M.; Sadick, AM. Exploration the sustainable design strategies of mass customised social housing for saving energy with the example of Phoenix Response house project in Geelong Australia. 2022; 9TH ZEMCH Conference 2022, Bangalore, India, 3-5 Nov 2022, Bantanur, S.; Noguchi, M, 2022.


CHAPTER 3
Building Energy, Performance & Technology
3D PRINTING EVALUATION OF OFFICES IN UAEU CAMPUS.

Due to UAEU’s future prospect which is always seeking for more creative and modern technologies, in this research we will discuss the potential of having 3D printed offices in UAEU campus. This research paper examines the option of 3D printing technology for improving the evaluation of offices in the UAEU campus. 3D printing is a new revolution in construction and sustainable design and according to the UAE government’s vision and interest in this technology that stems from the advantages that this technology will offer, this technology has several benefits such as less material waste, higher construction speed, less expenses. 3D printing technology might lead the sustainable urbanism to successful developments by creating sustainable cities and neighborhoods. This technology meets most of the future design requirements such as being affordable, Eco-friendly, flexible, stylish and healthy. 3D printing got the attention of many developed countries such as Singapore, China and UAE. The office of the future in Dubai is one of the great examples of 3D printed offices which gives a good impact on the future of this technology. This paper will study the location and climate effect on the construction using 3D printing method, also will have a method comparison between conventional construction and 3D printing and will evaluate the results and outcomes of the modeling and energy simulation and studying the cost and time analysis of this technology. The results of the present investigation demonstrate the positive effects of this technology on the construction sector and offices evolution.

Keywords
3D printing, UAEU offices, evaluation, construction, materials

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1. Introduction

3D printing technology has been around for the past few decades, but only recently has it started to become more widely used. It has become an invaluable tool for businesses and individuals in a variety of industries, from manufacturing to engineering and architecture. The United Arab Emirates University (UAEU) is no exception, as it has begun to explore 3D printing for use in its offices and other areas of the campus.

This paper will take a look at the potential of 3D printing in UAEU campus offices and discuss the advantages, challenges, and tips for successfully implementing 3D printing in office spaces. We’ll also discuss the types of 3D printing technologies used in offices and the services available for 3D printing in UAEU campus offices. [1]

3D printing is a process of creating 3-dimensional objects from digital data. It uses a digital file as a blueprint and then builds up a physical object layer by layer. It can be used to create a range of objects, from toys and models to parts for cars and planes. Technology has been around since the 1980s, but it has only recently become more accessible and cost-effective. In recent years, 3D printing has become an essential tool for businesses and individuals in a variety of industries. It is being used to create products faster and with greater accuracy, as well as reduce costs and waste.

Slow production, poor quality, low safety, and a lack of competent personnel are all potential problems for the construction business. Several Japanese construction firms are turning to technology to help them cope with the manpower crisis. As a result, they created either single task robots to replace straightforward labor tasks or completely automated systems that can erect tall steel structures or steel-reinforced concrete structures from prefabricated parts. has led to the creation of 11 fully automated construction systems and more than 89 single-task construction robots.[2]

Although productivity, safety, and quality have all increased thanks to robotics, conventional construction methods are still used. It costs a lot of money to automate traditional construction methods like utilizing a robot to lay bricks. Hence, layered construction has emerged as the new option in the building sector.

The fundamental argument made in this essay is that, in addition to being situation-specific, the subject of the environmental impact of digital fabrication is complex and has a difficult answer. Examples that highlight potential significant material savings are given, however they are now more expensive to build than bulkier pieces with simpler designs. In fact, the potential for material efficiency is what sets digital concrete construction apart from conventional construction in terms of sustainability, a distinction that those working to advance the technology to this end.[3]

This is especially important because adoption of the technology based solely on cost-related factors would entail accepting a higher carbon footprint in exchange for lower labor costs. The current incentives for the implementation of digital concrete processes appear to be primarily cost-driven, related to formwork and masonry labor. Although this research is just concerned with the environmental impact of these technologies, there may still be additional societal benefits (or drawbacks) to them.

With 3D printing, architects may create buildings with a variety of oddball shapes that are difficult to construct using traditional construction methods. A diagram showing the relationship between architectural.

The construction industry consumes more than 40% of all raw resources. For a single-family home, for instance, the CC approach can minimize material waste from seven tons to nearly none. CC objects only employ material when necessary. Also, the conventional concrete process (CCP) of the concrete masonry unit produces a small percentage of the CO2 emissions that are now produced. Also, as a result of the growth of 3D printing, structural engineering is improving in the building sector in terms of materials and structural systems as follows. [4]

Traditional concrete varieties are not the most practical material for 3D printing because of predictable issues with aggregate jamming in the nozzle, compacting impediments, and the spacing restrictions caused by the installation of rebar and formwork. A growing number of research projects
are now focused on finding novel concrete materials or identifying existing concrete materials that can be used in 3D printing and have the necessary mechanical qualities to be continuously extruded and piled on top of one another. 3D printing offers a number of advantages for construction projects. It can be used to create complex shapes that are not possible with traditional construction methods, allowing for greater design flexibility. Additionally, 3D printing can reduce costs, as it eliminates the need for expensive tooling and manufacturing. It can also reduce waste, as it uses only the amount of material necessary to create the desired object. 3D printing also offers a faster way to produce parts and components, which can be a great time-saver for companies.

The United Arab Emirates University (UAEU) is one of the leading universities in the region and has been exploring the potential of 3D printing for use in its offices and other areas of the campus. The university has been pushing the boundaries of 3D printing technology and exploring the possibilities of using it in its research and development efforts. UAEU has already begun to use 3D printing to create prototype parts and components, as well as to produce parts and products for its research and engineering projects. 3D printing can be used to create complex shapes and objects that are not possible with traditional construction methods. For example, 3D printing can be used to create structures that are more efficient and sustainable, as it uses materials that are lighter and more durable than traditional construction materials. [6]

Lean construction, green building practices, and sustainability in the construction industry may all benefit from 3D printing technologies. This conclusion suggests that research in the field of 3D printing technology will become more important in the near future. The idea of contour crafting, which enables in-place printing of homes, may call for a fresh approach to architectural building design. The development of novel materials that are suitable for 3D printing while also taking sustainability concerns into account, materials in which conventional concrete constituents will be replaced with environmentally friendly ones, is required for this method. One of the main advantages for most architects may be the ability to construct buildings with complex shapes. Their inventiveness will enable them to overcome earlier challenges brought on by the limitations of conventional building procedures. [7]

There are a variety of 3D printing technologies available, and each one has its own advantages and disadvantages. The most common types of 3D printing technology used in offices are Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS). FDM is the most widely used 3D printing technology, as it is fast, cost-effective, and can create parts with a high degree of accuracy. SLA is also a popular technology, as it can be used to create parts with a high level of detail and accuracy. Finally, SLS is the most advanced 3D printing technology, as its c (Ibrahim et al., 2022) can create parts with an even higher level of accuracy and detail than FDM and SLA.

UAE has already used 3D printing technology to quickly construct a new successful office project (Dubai’s 3D Printed Office Building). It was a very effective project on many aspects such as reducing the labor costs by 50% to 80% and the construction waste by 30% to 60%.

UAE is motivated to open a 3D printing facility in Dubai by a few advantages. Time, money, the environment, and the number of people needed to complete the job can all be saved. The UAE intends to use 3D printing technology to create 25% of Dubai’s buildings by 2030. 3D printing is becoming increasingly popular in offices and other designs in the UAE. It offers a number of advantages, including faster production times, reduced costs, and the ability to create complex shapes and objects. Additionally, 3D printing can help reduce waste, as it uses only the amount of material necessary to create the desired object. However, there are also some challenges associated with 3D printing, such as the cost and accuracy of the technology. With the right planning and implementation, 3D printing can be a valuable tool for businesses and individuals in a variety of constructions. [8]
2. Materials and Methods

After a deep literature review and critical readings about the technology and previous studies which provided useful information about the digital fabrication application in sustainable construction and highlight new ways of research methodologies. Using the science gateways such as google scholar, searching keywords such as (Digital fabrication, sustainability, digital construction, Dubai vision in building construction, challenges of digital fabrication,) investigating the subject in depth and the information that has been taken from journals

Starting by making sketches for office buildings as potential for applying the 3D printed office in (UAEU) drawing an office building, evaluating two concepts then making a decision matrix for the two concepts then choosing one of them after that we start developing plan for the chosen concept and making simple 3D model for it using 3D max. will study the duration and climate effect on the construction using 3D printing method, the paper will evaluate the design alternative and also will have a method comparison between conventional construction and 3D printing and will evaluate the results and outcomes of the modeling and energy simulation and studying the cost and time analysis of this technology as shown in Figure 1.

The main steps of the study are:
Location and climate analysis
Design alternative / selection
Modeling and energy simulation
Building technology comparison and evaluation
Cost and time analysis

2.1. Site and Weather analysis

UAEU is located in United Arab Emiratis (AL AIN City) in special location as shown in Figure 2 which is allowing the building to have a massive area that can serve all the colleges students and to make their studying life easier. For this research we need to locate extra offices for the university which is 3D printed offices. Tropopsamments, a soil type with low dunes and a wide range of compatibility, is present here. Despite the fact that the soil is not very sturdy, it does not require any special care. The choice is to employ a particular kind of shallow foundation, which will satisfy the need. So that make the applying of the 3D printing much easier. In the topography part we will have flat land and no hills.
This area is totally straight and has no bumps or hills.

![Figure 2. al ain city and neighborhood analysis. (a) Al Ain city satellite map (b) UAEU city satellite map.](image)

A fence that now encloses the area has to be taken down, and students need a new entry. The sound of the bus is the only source of noise because a building surrounds the place. As a result, the structure needs soundproofing, and some fountains can be placed to lower the noise level in the area.

Al Ain is around 120 kilometers south of Dubai and 160 kilometers east of Abu Dhabi, the country’s capital. The city’s climate is dry and hot with scorching summers from June to September and cool winters from November to March. Spring and autumn last anywhere from one to two months. The annual temperature ranges from 38 to 42 degrees Celsius in the summer to 24 to 26 degrees Celsius at its coldest. As it shown in Figure 3 the temperature, the humidity, the wind speed and the rainfall rates as shown in Figure 4.

![Figure 3. (a) temperature and (b) humidity in Al Ain city.](image)
2.2. Design process

The design process started from sketches for the office concept as shown in Figure 5 then out of zoning and having a good Design Decision Matrix the design was confirmed based on the study that has been done, after this step the next one was start drawing the plans as shown in Figure 6 and Figure 7 for the office using AutoCAD and start to develop the spaces and the details of the building to go for the 3D modeling for the building using 3D MAX.

Figure 4. (a) wind rose and (b) rainfall rates in Al Ain city.

Figure 5. (a) concept 1 sketch (b) concept 2 sketch

Figure 6. Concept 1 architectural plan.

Figure 7. Concept 2 architectural plan.
After studying the two concepts to choose the more suitable concept for the office based on the design decision matrix which can help to take the best option by considering architecture, sustainability, cost, quality and the building performance as shown in Table 1. The main objective evaluation factor for the architecture was 30% and for sustainability 30% the cost was 20% the quality and performance 10% for each design criteria and the weight factor for the two concepts.

Table 1. the design decision matrix for the two concepts

<table>
<thead>
<tr>
<th>MAIN OBJECTIVE</th>
<th>Main Objective Evaluation Factor</th>
<th>DESIGN CRITERIA</th>
<th>Design Criteria Evaluation Factor</th>
<th>Weight Factor</th>
<th>Concept 1 Score</th>
<th>Weighted Score</th>
<th>Concept 2 Score</th>
<th>Weighted Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architecture</td>
<td>30%</td>
<td>Site Optimism</td>
<td>25%</td>
<td>7.50%</td>
<td>9</td>
<td>0.68</td>
<td>9</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Structure</td>
<td>25%</td>
<td>7.50%</td>
<td>5</td>
<td>0.38</td>
<td>8</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Appearance</td>
<td>25%</td>
<td>7.50%</td>
<td>6</td>
<td>0.45</td>
<td>10</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MEP</td>
<td>25%</td>
<td>7.50%</td>
<td>8</td>
<td>0.60</td>
<td>8</td>
<td>0.60</td>
</tr>
<tr>
<td>Sustainability</td>
<td>30%</td>
<td>Renewable Energy</td>
<td>25%</td>
<td>7.50%</td>
<td>10</td>
<td>0.75</td>
<td>10</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Waste Management</td>
<td>25%</td>
<td>7.50%</td>
<td>8</td>
<td>0.60</td>
<td>9</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Recyclability</td>
<td>25%</td>
<td>7.50%</td>
<td>8</td>
<td>0.60</td>
<td>10</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Safety</td>
<td>25%</td>
<td>7.50%</td>
<td>8</td>
<td>0.60</td>
<td>9</td>
<td>0.68</td>
</tr>
<tr>
<td>Cost</td>
<td>20%</td>
<td>Construction Cost</td>
<td>50%</td>
<td>10.00%</td>
<td>7</td>
<td>0.70</td>
<td>8</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Material Cost</td>
<td>50%</td>
<td>10.00%</td>
<td>8</td>
<td>0.80</td>
<td>6</td>
<td>0.60</td>
</tr>
<tr>
<td>Quality</td>
<td>10%</td>
<td>Construction material quality</td>
<td>40%</td>
<td>4.00%</td>
<td>10</td>
<td>0.40</td>
<td>10</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Materials Durability</td>
<td>35%</td>
<td>3.50%</td>
<td>9</td>
<td>0.32</td>
<td>9</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Materials Reliability</td>
<td>25%</td>
<td>2.50%</td>
<td>9</td>
<td>0.23</td>
<td>9</td>
<td>0.23</td>
</tr>
<tr>
<td>Performance</td>
<td>10%</td>
<td>Easy to use / User friendly</td>
<td>25%</td>
<td>2.50%</td>
<td>9</td>
<td>0.23</td>
<td>7</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Easy to maintain</td>
<td>35%</td>
<td>3.50%</td>
<td>9</td>
<td>0.32</td>
<td>7</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multi- Comfort (Thermal, Visual, Acoustic, &amp; Indoor Air Quality</td>
<td>40%</td>
<td>0.04</td>
<td>9</td>
<td>0.36</td>
<td>10</td>
<td>0.40</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100.00%</td>
<td>7.99</td>
<td></td>
<td>8.64</td>
</tr>
</tbody>
</table>
Based on the design decision matrix the concept (2) is the preferable design based on most of the variables that the matrix studied so it will be the design that this paper will compare the conventional construction and the 3D printing technique of construction and its curvy shape will be a good example for the 3D printing power on creating complex design. The following figures Figure 8 to Figure 11 is the sections elevations and the 3D views of the office building.

**Figure 8.** Showing section A-A and section B-B.

![Figure 8](image1)

**Figure 9.** The east elevation of the building.

![Figure 9](image2)

**Figure 10.** The north elevation of the building.

![Figure 10](image3)
3. Results

The comparison between the 3D printing and the conventional construction in many aspects in this paper will compare the type of materials used in both methods, the time will each can take and the cost of both methods in Table 2. the comparison is between the material types used in the conventional construction and giving a brief about each material and the 3D printing materials used in case studies and having a 3D views that showing the paper office case as exploded model showing the details and the differences for both cases in Table 3. the table is showing the cost study for the office building as conventional construction by having the material and the quantity of each material to get the total cost per M2 of the model office. Expected cost is estimated by having the case studies showing the cost and the area of each case to estimate the total cost of the model offices if it’s 3D printed per M2 to get a reasonable comparison as shown in Table 4. And at the end the composition will be clear by looking at the time and the cost and using the timeline for the three case studies as shown in Table 5. Will give the estimation of the total price and the time each method will take and make the comparison much easier.

Table 2. The comparison between the materials of conv. construction and 3D printing.

<table>
<thead>
<tr>
<th>Conventional construction</th>
<th>3D Printing method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete – Concrete is the most common building material used in almost all kinds of constructions. It is a composite material from fine and coarse aggregate that is usually mixed with a binder.</td>
<td>BUILDING ON DEMAND IN COPENHAGEN (COBOD) Material: Concrete mix consisting of cement, sand and other additives.</td>
</tr>
<tr>
<td>Steel – Steel is a reinforcement construction material. It is a composite material made from alloys of carbon and iron. Steel is known for its high strength and functionality.</td>
<td>WASP: GAIA Material: Natural material mix consisting of 25% soil, 40% straw chopped rice, 25% rice husk, and 10% hydraulic lime.</td>
</tr>
<tr>
<td>Stone – Stone is actually a long-lasting building material. Many of the most ancient buildings in the world are made of stone. Its texture is versatile, we commonly use stones for walls and flooring</td>
<td>TVASTA: ROOM MODULE Material: Concrete mix based on ordinary Portland cement, but with lower water-cement ratio and consisting of cement, sand, and other additives.</td>
</tr>
<tr>
<td>Wood – Wood is actually to the oldest construction material. Most often, it is naturally available and is cost-efficient. These are molded into desirable shapes for construction of walls</td>
<td>APIS COR: RESIDENTIAL HOME Material: Concrete mix made up of cement, sand, geopolymer, sand and other additives.</td>
</tr>
<tr>
<td>Brick/ Masonry – For masonry works, there are rectangular blocks used. Bricks are traditionally made from heated and dry clay. It is important to understand that they have high compression resistance and will break easily.</td>
<td>WINSUN: WAVE BUILDING Material: Concrete mix made up of cement, sand, fiber and other additives.</td>
</tr>
</tbody>
</table>
Table 3. The cost of the materials of conventional construction.

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost</th>
<th>Quantity</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>concrete 40 N opc</td>
<td>210DHS/M3</td>
<td>34.32M3</td>
<td>7207.2</td>
</tr>
<tr>
<td>concrete 40 N SRC</td>
<td>220DHS/M3</td>
<td>34.32M3</td>
<td>7550.4</td>
</tr>
<tr>
<td>steel for reinforcing</td>
<td>2500DHS/TON</td>
<td>N/38.64M3/13.6TO</td>
<td>34000</td>
</tr>
<tr>
<td>Cement</td>
<td>13DHS/BAG</td>
<td>3 BAG</td>
<td>39</td>
</tr>
<tr>
<td>China plywood 18mm</td>
<td>70DHS</td>
<td>4 M2</td>
<td>280</td>
</tr>
<tr>
<td>white wood 4<em>4inch</em>13F</td>
<td>1800M3</td>
<td>2M3</td>
<td>3600</td>
</tr>
<tr>
<td>Concrete Hollow Block</td>
<td>20 DHS per piece</td>
<td>110.5M2</td>
<td>800</td>
</tr>
<tr>
<td>Bricks 20 CM</td>
<td>2 DHS per piece</td>
<td>181.4M2</td>
<td>49</td>
</tr>
<tr>
<td>sand one car (3M)</td>
<td>250DHS</td>
<td>1 car</td>
<td>250</td>
</tr>
<tr>
<td>Stainless Steel Sheet 5mm</td>
<td>1500DHS per sheet</td>
<td>2 Sheet</td>
<td>3000</td>
</tr>
<tr>
<td>Normal steel sheet 4mm</td>
<td>300DHS per sheet</td>
<td>3 sheet</td>
<td>900</td>
</tr>
<tr>
<td>paint material +work</td>
<td>10DHS per meter</td>
<td>181.4M</td>
<td>1814</td>
</tr>
<tr>
<td>stone</td>
<td>35DHS per meter</td>
<td>28.4M</td>
<td>994</td>
</tr>
<tr>
<td>water 2000L</td>
<td>150DHS</td>
<td>4000L</td>
<td>300</td>
</tr>
<tr>
<td>Passco 8 cm</td>
<td>30DHS</td>
<td>227.6M2</td>
<td>6828</td>
</tr>
<tr>
<td>Aluminum work windows &amp; doors</td>
<td>550DHS/M2</td>
<td>16.86M2</td>
<td>9273</td>
</tr>
<tr>
<td>Wooden doors</td>
<td>1000DHS/M2</td>
<td>8M2</td>
<td>8000</td>
</tr>
<tr>
<td>ceramic fixing price by M2</td>
<td>22DHS/M2</td>
<td>162m2</td>
<td>3564</td>
</tr>
<tr>
<td>Steel fixer for construction</td>
<td>60DHS/M3</td>
<td>38.64M3</td>
<td>2318.4</td>
</tr>
<tr>
<td>Grand total (AED)</td>
<td></td>
<td></td>
<td>90767</td>
</tr>
</tbody>
</table>

COST PER M2 = 553.45/M2

Table 4. The timeline of three case studies.

<table>
<thead>
<tr>
<th>TIMELINE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dubai municipality 3d printed building</td>
<td>90 days</td>
</tr>
<tr>
<td>The tallest 3d printed building in the world is now in Saudi Arabia</td>
<td>26 days</td>
</tr>
<tr>
<td>Office of the Future DUBAI</td>
<td>17 days</td>
</tr>
</tbody>
</table>
Table 5. The estimated time for the conventional and the 3D method.

<table>
<thead>
<tr>
<th></th>
<th>CONVENTIONAL</th>
<th>3D PRINTING</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ESTIMATED TIME FOR THE PAPER CASE STUDY OFFICE</strong></td>
<td>180 days</td>
<td>5 to 7 days</td>
</tr>
</tbody>
</table>

Conclusion

Based on the above results, time of construction, cost and technology used, the 3D printing of such offices seems to be the best solution. This kind of technology is expanding more and more in the Middle East region. This research aimed to show the advantages of such a type of construction.

The example taken into study is one floor, future work shall be done in understanding how this technology can be applied in multiple floors in the country. Furthermore, further investigation shall be done to evaluate the use of this technology in housing programs in the city of Al Ain, Abu Dhabi.

The main difficulties encountered were the tools used to calculate the volume of the materials. Additionally, the current examples do not have enough information for the research to investigate further this innovative technology.

However, this study may be relevant to UAEU decision making and local authorities in the city, where building low-rise units might be more efficient with innovative technology such as 3D printing.

References

Autor Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “conceptualization, H. Ajiba and L. Bande.; methodology, L. Bande.; software, H. Ajiba.; validation, H. Ajiba.; formal analysis, H. Ajiba.; investigation, H. Ajiba.; resources, H. Ajiba.; data curation, L. Bande.; writing—original draft preparation, H. Ajiba.; writing—review and editing, L. Bande.; visualization, H. Ajiba.; supervision, L. Bande.; project administration, L. Bande.; funding acquisition, L. Bande.”

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Conflicts of Interest: The authors declare no conflict of interest.
The creation of architectural ideas is a key competence that the architecture students must acquire, which is achieved through hand drawing as well as the development of creativity and Spatial Skills throughout their studies. This research argues that architectural conception drawing mediated by Immersive Virtual Reality (IVR) enhances both capabilities and reduces differences between new and senior students in architecture. To demonstrate the hypothesis, a convenience sample of 28 students from Universidad Nacional de San Agustín de Arequipa participated in an experiment. Both groups drew an architectural idea using HMD and Tilt Brush software. Prior to this the level of creativity and Spatial Skills was evaluated using three standardized tests, and their IVR conception drawings were evaluated using two grade sheets. The results show that novices, despite having a lower average in creativity, stand out in fluency and experts in elaboration when creating in IVR. In the measurement of the levels of Spatial Skills, a very slight difference is observed, but novices develop better the three-dimensionality of the object in IVR. In conclusion, the utilization of IVR enables easy visualization and manipulation of three-dimensional drawings and enhances the achievement of creative ideas through conception drawing while minimizing the differences in Spatial Skills and creativity levels between novices and experts previously measured with standardized tests.

**Keywords**
Immersive Virtual Reality; Conception Drawing, Graphic Ideation, Tilt Brush, HMD, Architecture, Design.
1. Introduction

The construction of ideas in architecture is closely connected to drawings and the act of drawing. The drawing of ideas is considered a fundamental competency that architecture student must acquire. Traditionally, this competence is developed through hand drawing with pencil on paper, is achieved with practice in drawing and design workshops and with the development of the cognitive capacities of creativity and Spatial Skills (SS) throughout their academic journey. This research argues that drawing architectural ideas mediated by Immersive Virtual Reality (IVR) not only promotes creativity and the three-dimensional development of ideas, but also has the potential to minimize the disparities in these cognitive abilities between freshmen and seniors in architecture.

1.1. Creativity and the drawing

Four stages are recognized in the creative process: preparation, incubation, insight and verification. In preparation, data is collected and related ideas are sought. In incubation, the prepared material is elaborated and organized. Insight occurs when existing ideas are combined to form complex mental structures. In verification, the value of the idea is evaluated and its complete form is elaborated [1]. The creative process requires not only the conception of an idea but also the development of a complete response. In architectural design, the creative process employs methods such as drawing, which deploys the ability to design and develop visual language [2]. Techniques such as computer-assisted drawing have also been incorporated, which have made it possible to recognize the importance of the technologic support. For the drawing method, the freehand technique shows in tune with the movement of the hands on the paper and the stroke created, being that the movements of the hand feed creativity through several mechanisms of the nervous system [3]. Therefore, in the creative process, the method, the instrument and the technique must be taken into account, since they can limit or enhance creativity in the architectural design process.

1.2. Spatial Skills and the drawing

Spatial Capacity can be defined as the capacity to generate, retain, retrieve and mentally manipulate well-structured visual images and their parts in two- and three-dimensional space [4]. Among the three components of this cognitive ability is the Spatial Skill (SS) which can be measured with standardized psychometric tests. This research will use Carroll’s proposal [5] to measure it, which identifies two subcomponents: spatial visualization and mental rotation. SS are important in architecture for representing spatial ideas successfully and therefore for the creation of spaces and learning experiences [6]. Some authors link SS to the creativity needed for architectural design [7] by demonstrating that individuals with high SS excel in designing complex forms, while those with medium and low SS excel in simple additive approaches.

1.3. Conception Drawing

The process of generating an idea involves a "front-end" approach, in which partial and rudimentary representations are produced, evaluated, transformed, modified, refined and replaced by others, until their creator is satisfied with the results [8]. This active representational process gives rise to a special type of drawing that is known as “conception drawing” which was first introduced by Boudon and Deshayes [9]. They defined it as the drawing to conceive, grope, adjust and rectify, thus a reality-generating drawing, a conjectural and formative drawing of an architectural object that still exists only virtually [10]. Conception drawings are graphic expressions that act by concentrating abundant conceptual load and high symbolic codification that support extensive ideas, lines of action, or tentative proofs. They are configured as guidelines for subsequent actions, not being able to outline a definitive solution due to their low graphic codification, but they do generate discourses to achieve architectural responses [11].
1.4. Immersive virtual reality in the design process

IVR offers different possibilities to explore and express ideas in the design process compared to traditional methods [12]. It serves as a valuable tool for experiencing spaces through the creation of a strong sense of presence [13]. It allows immediate design feedback [14] and investigates the impact of spatial stimuli and the perception of architectural space [15]. Moreover, IVR strengthens experiential learning by allowing constructivism with first-person experiences and creating a sense of immersion, enabling students not only observe but also interact with their environment as a means of learning [16]. Also contributes to motivate students in the acquisition of knowledge [17], facilitates communication in the process of a design project and efficiently supports participatory design in decision making [18].

2. Materials and Methods

The methodological process is based on the correlation between creativity and SS in the creation of ideas through concept drawing in IVR (figure 1). To measure these aspects, three input instruments and two output instruments were utilized. The first input instrument was the Torrance Test of Creative Thinking (TTCT) which evaluated the level of creativity through drawings. This test assesses the components of originality, fluency, flexibility, and elaboration. Fluency measures the number of responses, flexibility measures the variety of responses, originality of the novel and unconventional responses, and elaboration measures the amount of detail. The test has a maximum running time of 30 minutes [19]. The second input instrument was the Mental Rotation Test (MRT) to measure the spatial rotation of objects through the recognition of blocks in three-dimensional perspective with different orientations [20]. The third input instrument was the Differential Aptitude Test: Spatial Relationships (DAT-SR) which evaluated spatial visualization recognizing two-dimensional figures and mentally constructing a three-dimensional mental image from them [21].

![Figure 1. Conceptual relationship of the literature review and methodological process](image-url)
The first output instrument was a grade sheet (CR-IVR) that assessed the creativity of the designed object in IVR taking the same four criteria of the TTCT (table 1). Some examples of the evaluated objects can be seen in figure 3.

**Table 1.** Grade sheet to assess the creativity of the designed object in IVR (CR-IVR)

<table>
<thead>
<tr>
<th>N°</th>
<th>Items</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Originality: novel and unconventional designed objects are shown</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Elaboration: many details that embellish and improve the designed object are shown</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Fluency: a large number of designed objects are shown.</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Flexibility: a high variety of designed objects are shown</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>40</strong></td>
</tr>
</tbody>
</table>

The second output instrument was also a grade sheet (SS-IVR) that evaluated the three-dimensionality of the same object based on four criteria (table 2): three-dimensionality that evaluates if the object is developed in all its dimensions and is not worked by flat faces; complexity, that measures if the object shows a high level of complexity without affecting its understanding and unity; depth, that evaluates if the object was created with mastery of depth perception; and scale, that evaluates if the object was constructed considering its perception at different scales. Some examples of the evaluated objects can be seen in figure 3.

**Table 2.** Grade sheet to assess the three-dimensionality of the designed object in IVR (SS-IVR)

<table>
<thead>
<tr>
<th>N°</th>
<th>Items</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Three-dimensionality: the object shows a development in all its sides and dimensions and is not only worked by flat faces</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Complexity: the object shows a high level of complexity without affecting its understanding and unity</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Depth: the object is constructed with a mastery of depth despite not having a physical support</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Scale: the object is constructed looking for its perception with the change of scales (smaller and bigger)</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>40</strong></td>
</tr>
</tbody>
</table>

For the experiment, 28 students from the architecture program of the Universidad Nacional de San Agustín de Arequipa in Perú were recruited. For the selection of the participants, a convenience sampling was carried out, seeking that the participants fit archetype 1 "novices": students who attended the first year of studies and who passed the subjects in architectural drawing and architectural design. And archetype 2 "experts": students who attended four years of the course and who passed all the subjects related to graphic expression and eight subjects of architectural design. A Google Forms questionnaire was used for recruitment, which also collected information on specific conditions such as color blindness, epilepsy, dizziness, nausea and migraine. These conditions also restricted participation in the experiment. Only 14 out of 80 first-year students and 14 out of 60 senior students met the conditions and agreed to participate in the experiment. The average ages of the novice and expert participants were 20.08 and 23.43 years respectively.

After recruitment and the signing of a consent form to participate in the research, two sessions were
scheduled. In the first session the three input instruments were applied for one hour, then proceeded for 15 minutes to the explanation and handling of the HTC Vive HMDs and Google's software for artistic drawing Tilt Brush. The first session ended with each participant using the equipment and software for 20 minutes. At the end of this session each participant was given the poem "El Viento" by Peruvian writer José María Eguren. No explanation was given beyond reading, understanding, and recognizing the feelings and sensations that this text generated.

The second session began with the explanation of the design theme: to generate an architectural idea for a “Livable Sculpture” that would allow them to experience the sensations of the poem studied. It was emphasized that the goal was not to produce a precise and finalized proposal but to develop an idea that could be further refined later. They were also asked to record the whole ideation process. In the IVR environment, participants were given 25 minutes to create three-dimensional drawings of their initial ideas. This was followed by a five-minute break to drink high-electrolyte fluid. They then continued for another 25 minutes to resume initial drawings, ending attempts, and finalize the idea. Figure 2 shows the students' IVR drawing process and the result obtained.

![Figure 2. The students creating their designs with de HMD HTC Vive and de Tilt Brush software and the obtained results.](image-url)
3. Results

The evaluation of creativity levels measured using TTCT shows on average a slight superiority in favor of the experts. In the disaggregate, novices stand out in originality and fluency in comparison with the expert who stand out in flexibility and elaboration (table 3).

**Table 3.** Test averages and scores obtained from the evaluation of the IVR designed object.

<table>
<thead>
<tr>
<th></th>
<th>Originality</th>
<th>Elaboration</th>
<th>Fluency</th>
<th>Flexibility</th>
<th>Total</th>
<th>Originality</th>
<th>Elaboration</th>
<th>Fluency</th>
<th>Flexibility</th>
<th>Total</th>
<th>DAT-SR</th>
<th>MRT</th>
<th>Spatial Skill Score (SS-R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novices (n=14)</td>
<td>42.57</td>
<td>8.79</td>
<td>19.50</td>
<td>10.29</td>
<td>78.45</td>
<td>6.29</td>
<td>5.71</td>
<td>8.29</td>
<td>5.43</td>
<td>25.71</td>
<td>40.37</td>
<td>24.04</td>
<td>34.14</td>
</tr>
<tr>
<td>Max score</td>
<td>255</td>
<td></td>
<td></td>
<td></td>
<td>255</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>50</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>

This trend is even more pronounced in the evaluation with CR-IVR, where novices, in addition to standing out in originality and flexibility, stand out significantly in fluency. As for the measurement of the SS levels, there is a very slight difference between the DAT-SR and the MRT, however, when evaluating the three-dimensionality of the designed objects, novices demonstrated a greater advantage (table 3).

For a better comparison of the TTCT values (maximum score 255) and the values of creativity evaluated...
with CR-IVR (maximum score 40), the TTCT values have been scaled to a maximum of 40. Figure 4 illustrates a correlation between the TTCT scores and the results of the CR-IVR. The comparison reveals that despite having a higher average TTCT score, the experts did not achieve as creative responses in IVR as the novices did. In novices the curve of TTCT values is steeper than the curve of IVR design results. This result suggests that the differences in creativity are narrowing in IVR context. Conversely, for the experts the curve of the results is steeper than that of TTCT. This shows that the more creative ones obtained a more creative design in IVR, and the less creative ones did not take advantage of the tool and obtained less creative designs.

![Creativity: scores in TTCT vs scores in IVR Design](image)

**Figure 4.** The evaluation of the creativity level using the TTCT and the CR-IVR (grade sheet in IVR)

The SS results evaluated with the DAT-SR compared to the SS-IVR scores show that there is a correlation between the spatial visualization levels and the mastery and outcome of the three dimensions of the designed object. Another result found in both groups is that the slope of the SS-IVR trend line is smoother than the slope of the DAT-SR test. See figure 5 for the flatter Novices and Experts IVR design score (SS-IVR) curves than the steeper Novices and Experts MRT curves. This result shows that the IVR environment reduces spatial visualization cognitive differences by making participants better understand and master the three dimensions. With the MRT there is also a correlation between the level of spatial rotation and the three-dimensionality of the final object.

![Spatial Skills: scores in MRT, scores in DAT-SR, scores in IVR Design](image)

**Figure 5.** The evaluation of the SS levels using DAT-SR, MRT and the SS-IVR (grade sheet in IVR)
In this case, it is a little steeper the curves of the values obtained in the MRT than the SS-IVR. Figure 5 also shows that students with lower values in the MRT (see the right end of the curves) achieve much better levels of three-dimensionality of the designed object in IVR.

4. Discussion

IVR offers different possibilities to explore and express ideas in the drawing and design process compared to traditional methods due to immersion, presence and immediate design feedback [14]. These benefits have been reflected in this research by introducing IVR as a tool for architectural conception drawing. It has been found that using HMDs with haptic controls on both hands and the use of the artistic application Tilt Brush, students have shown greater creativity in CR-IVR than their TTCT values. IVR has enhanced creativity particularly in the fluency and elaboration components in both novices and experts. But it has been fluency which has been enhanced with more emphasis in the novices probably since in the first year the design process itself is studied in great detail and applied to small architectural objects. In contrast, experts learn over the years that almost any idea is good if it can be developed properly, which may be limiting their level of fluency but further developing their elaboration component. This has been the case in the experimentation; the experts have slightly outperformed the novices in the elaboration of their ideas in IVR.

Although expressing creative ideas does not require high SS levels, for Architectural Conception Drawing which involves the creation of a three-dimensional object, this cognitive skill is required to achieve complex three-dimensional responses rather than simple additive forms [7]. IVR has enabled novices and experts both to develop a highly complex three-dimensional concept drawing. In IVR it is possible to directly visualize and manipulate the objects that are being created, and it is exactly the skills which are measured in DAT-SR and MRT. It is clear that both groups have taken advantage of the benefits of the IVR to execute conception drawings with mastery of three-dimensionality, complexity, depth, and scale.

This research has an exploratory scope with an experimental design. A methodology was designed with a non-probabilistic sampling therefore it is not intended to generalize the results to the total population under study. However, the findings of this research show clear evidence of an imminent paradigm change in the conception drawing in architecture. For future research, it is suggested to design with probability sampling, control groups and longitudinal designs to determine more significant relationships in this area of knowledge.

5. Conclusions

This research concludes that an IVR environment using HMDs with haptic controls and the Tilt Brush artistic drawing application is the optimal tool to visualize and directly manipulate three-dimensional drawings and to achieve creative ideas through the conception drawing of a small architectural space. This conclusion is reached after an experimentation carried out with 28 students from the Universidad Nacional de San Agustín de Arequipa in Peru, 14 novices and 14 experts after being evaluated with three input instruments (TTCT, DAT-SR and MRT) and two output instruments (CR-IVR and SS-IVR). The IVR environment is favorable for fostering all four components of creativity through conception drawings. However, two components are most favored: fluency in novices and elaboration in experts since easy, real-time, freehand drawing in IVR is unrestricted by space, technique, or mental mastery of three-dimensionality. Also, the IVR environment is favorable for visualizing and directly manipulating the objects being created in such a way as to achieve conception drawings with mastery of three-dimensionality, complexity, depth, and scale. This has been more exploited by the novices but both groups have shown a mastery in the skill of generating and
manipulating complex and well-structured three-dimensional objects over their measurements with DAT-SR and MRT. It is considered as a future work to carry out an experimentation with control groups and in different time intervals to obtain more conclusive results.

Autor Contributions: Introduction, Hugo Gómez-Tone HGT, Edith Gabriela Manchego-Huaquipaco EGMH and Cinthya Butrón-Revilla CBR; Methodology HGT, EGMH and CBR; Experimental Design, HGT, EGMH, CBR and John Bustamante-Escapa JBE; Data collection, HGT, EGMH, CBR, JBE and Betty Valencia Anci BVA, Results, JBE and BVA.

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References


Building a Net Zero Energy Home: A Case Study with Wikihouse Prototype in Chile

Human activity, mainly in the construction sector, is the main cause of the increase in greenhouse gas concentration in the atmosphere, which accelerates climate change. The construction sector uses about 40% of the world's energy and generates one third of global greenhouse gas emissions. In Chile, 66.2% of households have energy efficiency problems, mainly due to the fact that 66% of these houses were built before the implementation of thermal regulations in 2000, and multidimensional poverty that prevents energy efficiency actions.

WikiHouse is an open-source system aimed at designing and constructing houses with optimized material usage and reduced assembly time, as well as offering affordable and creative housing designs. Its digital platform includes a library of house blocks, allowing users to cut the pieces through subtractive manufacturing and assemble them quickly and easily. In this context, the question posed in this work was: "How does this solution enable the achievement of high energy efficiency standards and address current housing problems while also meeting Chile's international commitments to achieve net zero energy by 2030 and carbon neutrality by 2050?"

In this work, a WikiHouse prototype was developed using the first version of the skylark 250 system in Temuco, Chile, which is located in a Mediterranean climate with mild summers, corresponding to a Csb climate based on the Köppen climate classification. The prototype was designed and built by a workflow using AutoCad, Fusion360 and a generic router CNC. It was evaluated using the software design builder, aiming to achieve high energy efficiency standards, net zero energy, and carbon neutrality using low-impact environmental materials. The main results show the feasibility of building under a design for manufacturing and assembly approach using more readily available technology while achieving useful energy consumption to implement the concept of net zero energy on a large scale.

Keywords
DFMA; WikiHouse; Net Zero.
1. Introduction

Human activity, mainly in the construction sector, is the main cause of the increase in greenhouse gas concentration in the atmosphere, which accelerates climate change. The construction sector uses about 40% of the world’s energy and generates one third of global greenhouse gas emissions [1,2]. In Chile, a significant proportion of homes face energy efficiency issues, primarily due to the fact that 66% of these homes were constructed before the introduction of thermal regulations in 2000 [3]. This has resulted in a significant environmental impact in the central-southern region of Chile, as the majority of households rely on biomass combustion for heating, leading to high concentrations of particulate matter both indoors and outdoors [4–6]. Consequently, the government has implemented air pollution control plans in various municipalities, with one of their key strategies being stricter thermal regulations. This has consequently increased the demand for thermal insulation materials and sparked an interest in the development of new environmentally-friendly insulation materials [7–9]. However, in recent years, the housing deficit has compounded this issue, creating a significant challenge. In the context of digitalization of the economy, this challenge also presents a great opportunity to address housing needs in a comprehensive manner, with a focus on industrialization, digitization, and sustainability as key pillars of future construction [10].

In this context, this study explores the use of the Wikihouse system in its recent 2022 Skylark version and its potential application in Chile to align with the country’s current guidelines and commitments in building construction. These include targets such as achieving net-zero emissions by 2030 and carbon neutrality by 2050. By examining the suitability of the Wikihouse system within this framework, this research aims to contribute to the sustainable and environmentally responsible development of the construction sector in Chile.

2. Materials and Methods

2.1. Prototype Skylark 250

The prototype design was based on the WikiHouse Skylark 250 v0.1 series M model, with a usable area of 14.88 m² (Figure 1) in Temuco, Chile, which is in a Mediterranean climate with mild summers, corresponding to a Csb climate based on the Köppen climate classification. The blocks were downloaded from the database on the wikihouse website [11], and the design was created using Sketchup software. The cutting programs for each element were created using AutoCAD and Fusion 360 software. The cutting was performed on a 3 kW CNC Router machine. This configuration includes the tool path, with a feed rate through rotational and translational movements at a spindle speed of 18,000 rpm, using an 8 mm diameter carbide end mill. The board used was an 18 mm thick structural plywood from a local company 40 km away from the workshop. Finally, the pieces were machined to form the different blocks that make up the construction solution. The assembly was done manually, starting with the floor. It consisted of 6 floor blocks, each measuring 0.38 x 0.60 x 0.318 m. Then, 23 wall blocks measuring 2.40 x 0.60 x 0.318 m were installed on the 4 facades, along with a door block measuring 2.40 x 1.20 x 0.318 m, a window measuring 2.40 x 0.60 m, and another window measuring 3.60 x 1.80 m. The ceiling, on the other hand, has the same characteristics as the floor, and a roofing solution was installed on top of it.
2.2. Hygrothermal analysis

The hygrothermal analysis of the construction solution was conducted using the Ubakus tool. The elements comprising each section of the modular system were inputted into the tool along with the climatic details of Temuco, Chile. This platform allowed for obtaining the thermal transmittance of the structure W/(m²K) and other indicators of its behavior. The indoor temperature was 20 degrees Celsius, with a relative humidity of 60%. Meanwhile, the outdoor temperature was 3.9 degrees Celsius, with a relative humidity of 96%, as suggested by the Ministry of Housing and Urbanism of Chile.

2.3. Dynamic energy performance

Based on the thermal transmittance obtained from Ubakus, a dynamic energy simulation was performed using Design Builder version 7 software. The occupancy was considered with two people, and the lighting load was set at 2 W/m². An air infiltration rate of 0.6 ACH50 and a ventilation rate of 0.3 ACH with a 70% efficiency heat recovery system were considered. For the windows, a triple glazing of 4/12/4/12/4e with a U-value of 1.191 was considered. Through this process, the required energy demand for heating and cooling of the prototype was obtained in kWh/year and normalized by area. To estimate the total electrical energy consumption, a 9000 Btu/hr split-type air conditioning unit with a heating coefficient of performance (COP) of 3.63 and an energy efficiency ratio (EER) of 3.23 was taken into consideration. Additionally, for domestic hot water, a 50-liter storage tank with a demand of 3.57 liters per square meter per day was considered.

2.4. Solar power generation

To estimate the solar energy that could be generated for the prototype, the solar explorer web tool was employed. The analysis considered a basic monofacial model with a panel temperature coefficient of -0.45%/°C. The installation characteristics included a fixed tilt arrangement and an isolated structure mounting type. The tilt angle was set at 31°, and the azimuth was -21°.
3. Results

3.1. Prototype Skylark 250

The prototype was constructed according to the design. The pieces were manufactured and stored in the workshop to be later transported to the construction site, where they were assembled (Figure 2 (a) and (b)). Some modifications to the original system were made. The most significant one was the elimination of the END elements, which required creating special assembly pieces against the floor and ceiling, as well as modifying some wall elements so that they could be joined externally with ties, as shown in Figure 2 (c). This change allowed for reducing 11 panels in the model and saving 8 hours of execution. For the prototype, 83 panels were used, with a total of 61.4 hours of work. The execution time considers a proportion of 30% for manufacturing and 70% for on-site assembly.

![Figure 2. (a) Manufactured parts stored, (b) Blocks into the construction site, (c) Corner modification](image)

3.2 Hygrothermal analysis

Figure 3 (a) depicts the wall construction solution based on Wikihouse Skylark 250. To ensure proper hygrothermal performance, a vapor barrier was incorporated on the interior, accompanied by a hydrophobic membrane on the exterior. As insulation, locally sourced polyurethane foam waste material was utilized, applied through a blow-in method. The resulting thermal transmittance, under the analyzed conditions, amounted to 0.13 W/m²K, effectively preventing condensation.

Figure 3 (b) showcases the floor construction solution derived from WikiHouse Skylark 250. To achieve optimal hygrothermal performance, a vapor barrier with a sd value of 25 m was implemented on the interior side. For insulation, polyurethane waste material from a local industry was employed in foam form, installed through a blow-in method. The thermal transmittance, without experiencing condensation, was measured at 0.10 W/m²K, aligning with the assessed conditions. The roof, similarly, adopted the same element as the wall, incorporating membranes of comparable composition. The roof’s thermal transmittance registered at 0.11 W/m²K.
3.3 Dynamic energy performance

Figure 4 (a) shows the resulting thermal balance from the analysis conducted using Design Builder. The highest heat loss occurs through windows with 633.4 kWh/year, followed by walls with 372.3 kWh/year. However, these values are quite low, as can be observed when compared to the solar gains of 1138.8 kWh/year.

In Figure 4 (b), the annual energy demand to maintain a comfortable indoor environment in the prototype can be observed. For cooling, it would be 215.7 kWh/year (14.98 kWh/m² year), and for heating, it would be 381.6 kWh/year (26.50 kWh/m² year).

3.4 Solar power generation

In Figure 5 (a), a graph is presented displaying the annual electrical consumption of 634 kWh and solar generation of 1220 kWh. The solar generation takes into account an installed capacity of 1 kW, with an inverter capacity of 1 kW, an inverter efficiency of 96%, and a photovoltaic system loss factor of 14%.

On the other hand, Figure 5 (b) depicts the theoretical monthly consumption of hot water, lighting, heating, and cooling, as well as the monthly solar generation potential.
4. Discussion

The design stage using the Wikihouse Skylark system as a base proved to be a dynamic experience, easy to adapt to different architectural requirements, and, above all, demonstrated to be an efficient system in terms of speed for machining and assembly, allowing for a gradual industrialization of the process.

The cavity it creates allows for the incorporation of insulation materials in thicknesses that achieve thermal transmittance values suitable for meeting standards such as Passivhaus or net-zero. At this point, it is important to note that these inherent characteristics of the system allow the design team to use this time to optimize processes and progress towards the integration of other efficiency or sustainability strategies.

In terms of energy performance, according to the conducted analyses, the prototype design is highly efficient in conserving energy. This enables the entire basic energy requirement of the prototype to be met by incorporating a low-power photovoltaic system.

Regarding future work, there are currently two ongoing lines of research. One is related to the final works on the prototype, where a monitoring system will be incorporated to validate the energy model and generate information on actual consumption. The other line of research focuses on optimizing the manufacturing of the Wikihouse system, exploring new manufacturing methods such as advanced robotics.

5. Conclusions

This study has demonstrated the high potential of utilizing the Wikihouse Skylark system in the construction of net-zero energy buildings. The efficient design and implementation of the prototype have shown promising results in terms of mechanization, assembly, and energy conservation.
Supplementary Materials: The following are available online at https://www.youtube.com/@jpcardenasr, shorts of the process.


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Conflicts of Interest: The authors declare no conflict of interest.

References


6. Jorquera, H.; Barraza, F.; Heyer, J.; Valdivia, G.; Schiappacasse, L.N.; Montoya, L.D. Indoor PM2.5 in


23 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).
Homes that are automated, remote controlled, and powered by solar panels are the homes of the future. At present there are very few self-sustaining houses and they can only be seen in the United States or some European countries, but they present several problems, one of them and the most important is the climate, since it does not have good solar radiation. This work aims to design, install and implement solar panels and automatic actuators to a house in the city of Arequipa - Peru, which will be controlled by an Amazon controller (Alexa) in order to take advantage of the good solar radiation of said city. and likewise demonstrate the economic and energy savings as it is a self-sustaining and hybrid home, since in cases of emergency the energy from the network can be used. This type of housing is ideal for adults, or people who have some physical limitation for their normal movement to activate any device within a home. Likewise, we can dispel thieves through immediate or preventive action in our home. The data obtained will be analyzed and the economic, energy savings, solar production and consumption of the public network will be shown. The analysis of the data in real time will allow us to observe the advantages of self-sustaining housing, likewise it will be possible to modify or maintain the parameters of our home through real-time maintenance from anywhere in the world.

Keywords
solar panels, self-sustaining houses, energy saving, economic saving, real time monitoring.
1. Introduction

Solar energy has become one of the most promising and rapidly growing sources of energy around the world. As we face increasing challenges in terms of climate change, depletion of natural resources, and reliance on fossil fuels, solar power has emerged as a clean, sustainable, and renewable solution to our energy needs. Today, solar energy plays an important role in the energy matrix of many countries. Many nations are investing in large-scale solar infrastructure, such as solar parks and photovoltaic plants, to generate electricity on a large scale. In addition, distributed solar energy systems, including rooftop solar panels and small local installations, are proliferating in communities and individual homes. Solar energy not only reduces our dependence on fossil fuels and helps mitigate the effects of climate change, but also has the potential to create green jobs and promote economic development. The solar industry has generated a wide range of job opportunities, from manufacturing and installation to research and development of new solar technologies. Renewable energy is rapidly gaining importance as an energy resource as the prices of fossil fuels fluctuate. At the educational level, it is therefore essential for engineering and technology students to have an understanding and appreciation of the technologies associated with renewable energy. One of the most popular renewable energy sources is solar power. Despite this energy potential available to us, the current use of solar energy is less than 5% globally. There are countries that are taking initiatives to stop using fossil fuels for solar applications. Germany is one of the countries that has shifted approximately 38% of its energy needs to solar power, and aims to completely stop its reliance on nuclear power and replace it with solar power by 2050. Also, most countries have abundant solar potential and can take a lesson from Germany. Solar energy is based on the capture of radiation from the sun and its conversion into electricity or usable heat. Solar technology has undergone significant advances in recent decades, leading to increased efficiency and cost reduction in solar energy production. Solar panels, which are the most common form of solar technology, have become more affordable and accessible to homes, businesses, and institutions around the world.

This paper is related to off-grid solar energy, also known as autonomous or grid-independent solar energy, which refers to the use of photovoltaic solar systems to generate electricity in areas that are not connected to the conventional electrical grid. Instead of relying on power distribution infrastructure, off-grid solar power systems allow users to independently generate and use electricity. Likewise, through this generation of solar energy, the resource will be used in the city of Arequipa, Peru, where radiation rates are 6,240KWh/m2-day [12]. With this radiation it will be possible to obtain a self-sustaining and automated home, with monitoring through an app 24 hours a day, that is, a 4.0 technology.

2. Materials and Methods

2.1 Materials

The materials used for the generation of solar electric energy to the house, are:

Table 1. Solar production materials

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Material</th>
<th>Unit power</th>
<th>Total power</th>
<th>Brand</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>Monocrystalline panels</td>
<td>505w</td>
<td>1,010w</td>
<td>Trina</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Solar controller-inverter</td>
<td>3,000w</td>
<td>3,000w</td>
<td>Growatt</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Wind-power generator</td>
<td>400w</td>
<td>400w</td>
<td>Esg</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>Wind-power controller</td>
<td>500w</td>
<td>500w</td>
<td>Esg</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>Gel batteries - @12V</td>
<td>300ah</td>
<td>300ah</td>
<td>Techfine</td>
</tr>
</tbody>
</table>

Source: Self made
The materials used for home automation, after generating electrical energy through solar panels, and converted into AC, are:

Table 2. Home automation materials.

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Material</th>
<th>Capacity</th>
<th>Brand</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>Circuit breaker DC</td>
<td>63A</td>
<td>Tomzn</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Circuit breaker AC</td>
<td>40A</td>
<td>Bticino</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Smart door lock with fingerprint</td>
<td>---</td>
<td>Moes</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>Smart power wall socket</td>
<td>16A</td>
<td>Moes</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>Smart plug socket</td>
<td>10A</td>
<td>Moes</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>Touch smart switch</td>
<td>10A</td>
<td>Moes</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>Zigbee gateway</td>
<td>---</td>
<td>Moes</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>Wifi smart gateway</td>
<td>Echo Dot 5</td>
<td>Amazon</td>
</tr>
</tbody>
</table>

Source: Self made

2.2 Methods

The house will be supplied by two types of renewable energy, through photovoltaic energy (solar panels) and through a wind generator. The connection is off-grid and hybrid which allows the house to always have electricity. The general connection is as follows in figure 1. During the day the solar panels provide energy to the house and in turn charge the batteries with the remaining energy that the house does not consume. The wind generator is a compensatory energy system for the home, taking into account that the wind speed in the city of Arequipa is 6 km/h on average, and it is irregular (not constant). The wind generator has been installed on the fifth floor (15 m high) to take advantage of the force of the wind. The diagram of the connections for the production of solar and wind energy is shown below with real photos:

The solar panels generate continuous electricity (43V, 11A, 505W) [12], which are connected to an intelligent hybrid controller and inverter that will allow analyzing the solar and wind production of the day, according to this analysis, solar production is taken as a priority to supply the home, as a second option the electricity provided by the wind generator and as a last option (that is, if it is at night) it
provides electricity through the 300Ah batteries (24V) [1]. The system is also connected to the public electricity network in case of any contingency or extreme case in which the solar and wind production is not sufficient, or also in the maintenance of the solar and/or wind system. In this case, the house will be supplied by the public network. This means that the house will never run out of electricity. In homes where public electricity is not available, that connection can be replaced by an internal combustion generator. It should be noted that the passage from one energy to another is not perceived by any device in the house, because it occurs between 15ms and 20ms.

2.2.1 Solar and power-wind production:

The formulas used to calculate solar panels and batteries are indicated in book [4] (pp. 36-60). Based on the formulas and calculations, we obtain the following results from table 3.

<table>
<thead>
<tr>
<th>Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Housing data</strong></td>
<td></td>
</tr>
<tr>
<td>Energy consumed by the house (Wh/day)</td>
<td>2500</td>
</tr>
<tr>
<td>Installation performance factor</td>
<td>0.723</td>
</tr>
<tr>
<td><strong>Solar Solar Panel Data</strong></td>
<td></td>
</tr>
<tr>
<td>Power of each solar panel (W)</td>
<td>505</td>
</tr>
<tr>
<td>Security factor</td>
<td>1.2</td>
</tr>
<tr>
<td>HSP</td>
<td>5.5</td>
</tr>
<tr>
<td>Energy provided by each solar panel (Wh)</td>
<td>2777.5</td>
</tr>
<tr>
<td>Necessary daily energy without safety factor (Wh/day)</td>
<td>3457.8</td>
</tr>
<tr>
<td>Necessary daily energy (Wh/day)</td>
<td>4149.4</td>
</tr>
</tbody>
</table>

**Battery data**
- Days of autonomy: 1
- Battery discharge (%): 0.5
- Installation voltage (V): 24

**Results**
- Number of solar panels: 1.5
- Solar inverter and controller power (W): 3000
- Wind generator power (W): 400
- Battery capacity (Ah): 345.8

The screen of the solar controller and inverter shows the real-time data of the connections as detailed below in image 2 (a). The wind controller screen shows the real-time data of the connections as follows in the image 2 (b). The maximum power to be consumed by the home is determined by the power of the controller and solar inverter. This data is very important because if we exceed the maximum power of 3,000W [3], the controller will show a fault and disconnect the AC load.

![Figure 2](image.png)

**Figure 2.** This image shows the screen of the solar and wind controller. (a) Solar controller display. (b) Wind power controller screen.
2.2.2 **Home Automation:**

The electrical energy generated from the solar panels and wind generator, is used in a detached house of 2 people in an automated way. To automate the home, it is necessary to connect the devices mentioned in table 2 to the home in a normal way through the "phase" and "neutral" cables as appropriate. These devices need to be connected to a communication protocol called "ZigBee". This protocol allows the devices to be operated even without an internet connection. It is important to have an internet connection to add the devices through the "smart life" mobile application. It is important that the internet router allows the connection of several devices at the same time for a quick interaction between the mobile application, devices and real-time monitoring. The mobile application "smart life" is shown below. Through an internet connection in the home and on the mobile phone, any device or appliance in the home can be turned on and off, which allows us to monitor and persuade any unwanted act on our home by strangers.

![Diagram of internet connection, wifi and ZigBee protocol of smart devices with router and gateway.]

Real-time monitoring and data storage of up to 2 months is done through a Wi-Fi modem connected to the solar controller and the home internet.

![Application "smart life" and Wi-Fi module.](image)

Figure 4. (a) Mobile application "smart life" to turn on or off automated home appliances. (b) Wi-Fi module connected to the solar charge controller connected to the internet to monitor and edit parameters in real time.
3. Results

In the city of Arequipa, the sunshine is observed from 6am to 6pm on average. The solar production is 1,000w as maximum power around 11am. The generation of electrical energy in a solar way is intermittent, it is not continuous.

![Figure 5](image1.png)

**(a)** Daily solar production. **(b)** Energy supply to the home in real time.

Real-time monitoring shows solar output from solar panels, current battery status, and load consumption. This production is regulated by the controller when the battery has a 100% charge. The following graph shows a summary of the year 2023 until June 15, on the consumption in KWh through the solar panels and the wind generator.

![Figure 6](image2.png)

**(a)** Monthly production of solar panels in KWh. **(b)** Daily production of solar panels, battery and household consumption.

In the figure 6, the solar production can be monitored in real time and we can observe the solar production (green color), the load consumed by the house (red color) and the battery supply to the house (purple color).

![Figure 7](image3.png)

**(a)** Maintenance by remote editing of parameters. **(b)** Summary of energy contribution.
Real-time monitoring allows us to obtain a summary of our collaboration with the planet in the amount of kilos of CO2 reduced (607.2Kg), forest reduction in the number of trees (83 trees) and standard carbon savings (607.2Kg). Likewise, the editing of parameters can be done through the cell phone or the web application, it is not necessary to go to the house to monitor on site or edit parameters on site. This maintenance methodology is called 4.0 and is the most modern today: and it can be used from anywhere in the world.

4. Conclusions

Through the energy obtained by the solar panels and wind generator, and converted into AC 220V, it is possible to supply single-phase electricity to a two-person single-family home. This house does not depend on public electricity, but on its own renewable energy. The maximum power that can be consumed in the home is 3,000W, which is determined by the controller and solar inverter. The batteries supply 3,600Wh to the home, that is, up to 50% of its capacity. This clean energy supplies smart devices which allow you to turn appliances on or off from anywhere in the world through an internet connection and installation of the "smart life", "alexa" and "shine phone" mobile applications. The monthly consumption of the single-family home is an average of 70KWh per month, which is clean energy and used to automate the home.

References


Methodological proposal for the integration of Building Information Modeling and Life Cycle Analysis for the calculation of the carbon footprint in building construction projects in Perú

Climate change is one of the main problems of our century and Greenhouse Gas (GHG) emissions are its main cause, considering that the construction industry is one of the biggest GHG emitters worldwide, it is imperative that this sector applies effective sustainability practices; currently there are various proposals for sustainability practices have been presented for the building operation stage, however these are limited because they are not framed within a holistic vision of the problem that includes an analysis of the entire life cycle of the building, in this sense, the present investigation, through a review of GHG quantification study cases and a theoretical, methodological and application comparison, proposes a carbon footprint calculation methodology that adapts to the context of Peruvian construction, takes as reference the framework of the life cycle analysis (LCA) that integrates with the Building Information Modeling (BIM) as a technological tool for the management of the diverse and large amount of project information required by the LCA. In order to validate the proposed methodology, GHG calculation was performed for the structures stage of the construction of an educational building, allowing to simulate the construction process and estimate that the building will generate 305.44 KgCO2eq/m2 in its construction stage from cradle to door, where 92.5% emissions correspond to the materials manufacturing stage and 57.5% incidence of this stage corresponds to ready-mix concrete since this resource has a long supply chain.

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Keywords
carbon footprint, life cycle assessment methodologies (LCA), planning and scheduling, building information modeling (BIM), 6D, construction, emission reduction strategy.
1. Introduction

The latest report of the Intergovernmental Panel on Climate Change [1], indicates that the changes in the climate that have been occurring in a widespread, rapid and increasingly intense manner, have turned climate change into a threat to political, economic and social stability of different peoples and nations [2], in this sense, the implementation of immediate, fast and large-scale sustainability practices that promote the reduction of greenhouse gases is required.

Considering that the construction industry is one of the main sources of GHG emissions, since it generates at least 39% of CO2 emissions [3], it is a priority that this sector incorporates effective sustainability practices, currently the sustainability practices in this sector are focused on optimizing the energy efficiency of the building operation stage, leaving aside the analysis of the manufacturing, construction and demolition stages, a situation that limits the effectiveness of the implementation of practices sustainability in this sector [4], given that depending on the type of infrastructure, site conditions and construction technology, the incidence of GHG emissions may vary between its different stages of the life cycle [5].

Thus, in order to design and implement effective sustainability practices in construction a comprehensive analysis of the impacts generated by construction must be based on, which is why this research focuses on the quantification and analysis of emissions GHG; As noted [6], currently there are several GHG quantification methodologies and standards, which may have an organizational or product-based approach [7], as is the case of the Perú, where the use of the quantification tool “Perú Carbon Footprint” [8], which is of an organizational approach, a situation that as indicated [9] [10], would limit the effectiveness of implementing sustainability practices in the construction sector, given that organizational strategies often do not reach an operational level due to the lack of a detailed analysis of the processes.

However, regardless of the selected methodology, it is verified that the basic framework is the Life Cycle Assessment (LCA) [11] [12] [13], because it allows a comprehensive analysis of the impacts generated in the different stages of the life cycle of a product [14]; LCA is developed in detail in the series of standards ISO 14040 [15], and generally presents three analysis approaches: (1) process-based, (3) economic input/exit (OIA) and (3) hybrid.

Considering that the main GHG quantification standards are based on LCA, [16] proposed the use of LCA to calculate the carbon footprint generated by precast concrete piles in the construction of a building in China, corroborating the high importance of the adequate selection of emission factors for the calculation of GHG.

Likewise, [4] present a comparative analysis of GHG emissions generated by conventional and prefabricated constructions in situ, where it is evident that the GHG incorporated in construction materials are the main GHG emitter and [17] [18] [19] in studies in Sweden, Iran and Malaysia, were able to identify that rudimentary constructions have lower environmental impacts compared to constructions industrialized due to less treatment of materials available.

Regarding the use of LCA in construction [5] [16] [20] [21] point out that although LCA is a useful method to assess the carbon footprint throughout the life cycle of a product, its use within the construction industry is still restricted due to the variety of materials, energy sources, suppliers, number of parts interested parties, site conditions and applicable regulations for each type of project, so it is recommended to integrate the LCA method with BIM in order to contribute to the proper management of project information, generating the necessary inputs for the correct implementation of the LCA.

Evaluating the benefits of the use of BIM in the implementation of good sustainability practices in construction, [22] proposed a methodology that allowed incorporating indicators of embodied energy, CO2 emissions, construction and demolition waste, in the BIM models, facilitating decision making related to environmental impact, likewise, [23] proposed an integrated design framework for the optimization of cost and carbon emissions of reinforced concrete structures with an optimization approach based on BIM.

In this sense, this research proposes a carbon footprint quantification methodology applicable to the
Peruvian construction context, which is taken as a reference framework for life cycle analysis (LCA) and is integrated with Building Information Modeling technology (BIM) as an information engine for the analysis of processes and the quantification of GHG emissions at the operational level.

2. Materials and Methods

The research started from an exhaustive review of the state of the art on the various methodologies and case studies of GHG quantification in the construction sector with the use of the words key: "Calculation, methodology(s), standard(s) and carbon footprint, product, ISO 14040, ISO 14067, construction, BIM", by using the Boolean operators (AND, OR and NOT) and by applying a 10 year old filter in the Scopus bibliographic database, selecting a total of 419 research articles.

Through the scope and content review technique, 15 study cases were selected that were submitted to a theoretical, methodological and application comparison in order to identify the potentialities and limitations of the methodologies used, know their databases and main contributions.

Considering the LCA framework, the contributions of the case studies and the use of BIM tools, the quantification methodology applicable to the context of Peruvian construction was designed. To evaluate the methodological proposal, a case study was selected that corresponds to the construction project of an academic building in Arequipa.

With the technical information of the project, the BIM modeling of the project was carried out using the Revit and Infraworks 2023 software at a level of development (LOD) 300, allowing to automatically estimate the amounts of work, which were integrated into the project budget with the Delphin Express software, which allowed prioritizing the analysis of the most incident resources and quantifying the GHG generated by including emission ratios in the BIM model, for the calculation of embodied energy and ratios of carbon footprint emission were used the Ecoinvent version 3.7.1 databases.

3. Results

3.1. Study of cases of application of carbon footprint quantification methodologies in the construction sector

From the review of the case studies, it was possible to identify that the LCA is the basic framework for the calculation of GHG and that, based on the case of Costa Rica, in Peru it is feasible to use the ISO 14067:2013 standard with adaptations to the context local, likewise, considering the complexity of the use of data in construction projects, BIM technology must be used to have an adequate management of the project information, finally it has been possible to identify that a key methodological factor in the LCA is the appropriate selection of GHG emissions databases, so the Ecoinvent version 3.7.1 databases will be used in the research. The main contributions of the case studies are summarized in Table 1.
Table 1. Main contributions of the research background of the analyzed case studies.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Main contribution</th>
<th>Methodology</th>
<th>Databases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xiao-Juan &amp; Yan-dan (2020)</td>
<td>HC = Activity level data x emission factor</td>
<td>LCA</td>
<td>Reports and research articles.</td>
</tr>
<tr>
<td>Xiao-Juan et al. (2021) &amp; Li et al. (2021)</td>
<td>Use of the BIM tool with ACV</td>
<td>LCA</td>
<td>Chinese government database</td>
</tr>
<tr>
<td>Eleftheriadis et al. (2018)</td>
<td>Integrated design to optimize costs and CO2 emissions</td>
<td>LCA</td>
<td>National inventories</td>
</tr>
<tr>
<td>Mercader et al. (2019)</td>
<td>Sustainability indicators in BIM model</td>
<td>LCA</td>
<td>Not shown</td>
</tr>
<tr>
<td>Kaewunruen et al. (2020)</td>
<td>LCA and BIM integration</td>
<td>LCA</td>
<td>UK database.</td>
</tr>
</tbody>
</table>

3.2. Carbon footprint quantification methodology proposal that integrates LCA and BIM tools applied to the case study

The research proposes the LCA as a framework with the limit of the “Cradle to the door” system based on the four methodological stages of the LCA: (1) Definition of objective and scope, (2) Analysis of the life cycle inventory, (3) Assessment of the impact of the life cycle and (4) Interpretation of the life cycle, incorporating the processes of modeling, calculation of quantities and analysis of resources within stages (2) and (3) of the LCA in order to manage the input data for the inventory analysis and carry out the calculation and evaluation of the carbon footprint considering three operational stages: (1) Manufacturing materials, (2) Transportation materials and (3) Construction process (see Figure 1).
3.2. Carbon footprint quantification methodology proposal that integrates LCA and BIM tools applied to the case study

The research proposes the LCA as a framework with the limit of the “Cradle to the door” system based on the four methodological stages of the LCA: (1) Definition of objective and scope, (2) Analysis of the life cycle inventory, (3) Assessment of the impact of the life cycle and (4) Interpretation of the life cycle, incorporating the processes of modeling, calculation of quantities and analysis of resources within stages (2) and (3) of the LCA in order to manage the input data for the inventory analysis and carry out the calculation and evaluation of the carbon footprint considering three operational stages: (1) Manufacturing materials, (2) Transportation materials and (3) Construction process (see Figure 1).

3.2.1. Definition of objectives and scope

Considering that the objective of the study is to calculate the GHG in the construction stage of building structures, the most incident items of this stage were selected as the study system, through the selection of items that represent 80 % of the direct cost of this budget.

The functional unit was defined as 1 m2 of built area, which represents the construction system and allows comparisons with other case studies. The system boundary considered a “cradle to gate” analysis with an assessment of the impacts on raw material extraction, transportation, material processing, transportation to the site and on-site construction.

3.2.2. Life Cycle Inventory Analysis

The process of quantifying the inputs to the study system began with the collection of project information, which served as the basis for the BIM modeling of the building with a level of detail or LOD 300, which means that the walls, ceilings, columns, beams and joints were represented in their shapes, sizes and final locations (see Figure 2), likewise, with the use of BIM model properties, the quantity of materials was extracted and by integrating the model with the Delphin Express software, the amount of resources needed per evaluation item was calculated.

Figure 1. Methodological proposal for calculating the carbon footprint.

Figure 2. (a) Case Study BIM Model and (b) location of the project in the environment
Considering the physical properties of the materials and using the embodied energy and carbon emission coefficients, the embodied energy in material production and carbon emissions were calculated as shown in Table 2.

<table>
<thead>
<tr>
<th>Items / Resources</th>
<th>Amount</th>
<th>Unit</th>
<th>Embedded Energy (GJ)</th>
<th>Total (t CO2eq)</th>
<th>% Emissions incidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete supply</td>
<td>2,116.50</td>
<td>m³</td>
<td>3,758.90</td>
<td>507.96</td>
<td>57.5</td>
</tr>
<tr>
<td>Formwork</td>
<td></td>
<td></td>
<td>70.61</td>
<td>5.16</td>
<td>0.6</td>
</tr>
<tr>
<td>Annealed wire #8</td>
<td>1,158.33</td>
<td>kg</td>
<td>10.89</td>
<td>0.51</td>
<td>0.1</td>
</tr>
<tr>
<td>2 1/2” - 4” Nails</td>
<td>1,178.17</td>
<td>kg</td>
<td>11.07</td>
<td>0.52</td>
<td>0.1</td>
</tr>
<tr>
<td>Tornillo wood</td>
<td>1,621.96</td>
<td>p²</td>
<td>15.31</td>
<td>1.10</td>
<td>0.1</td>
</tr>
<tr>
<td>Release agent</td>
<td>111.00</td>
<td>gln</td>
<td>10.19</td>
<td>1.37</td>
<td>0.1</td>
</tr>
<tr>
<td>Phenolic plywood</td>
<td>108.00</td>
<td>gln</td>
<td>23.15</td>
<td>1.67</td>
<td>0.2</td>
</tr>
<tr>
<td>Steel reinforcement supply</td>
<td></td>
<td></td>
<td>5,576.32</td>
<td>370.74</td>
<td>41.9</td>
</tr>
<tr>
<td>Annealed wire #16</td>
<td>10,379.88</td>
<td>kg</td>
<td>97.57</td>
<td>4.57</td>
<td>0.5</td>
</tr>
<tr>
<td>Steel rebar fy=4200 kg/cm²</td>
<td>267,281.93</td>
<td>kg</td>
<td>5,372.37</td>
<td>366.18</td>
<td>41.4</td>
</tr>
</tbody>
</table>

For the calculation of the emissions of the activities of transporting the materials, with the use of the Infraworks software, the project was located and calculated the transport distances of the materials to the work site (See Figure 3), considering the capacities of the equipment and an average transit speed of 15 km/h, the required machine hours and their fuel consumption, embodied energy and GHG emissions were calculated as shown in Table 3.

<table>
<thead>
<tr>
<th>Items / Resources</th>
<th>Number of trips</th>
<th>Transport distance (Km)</th>
<th>HM Required</th>
<th>Total Energy (GJ)</th>
<th>Total (t CO2eq)</th>
<th>% Emissions incidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete supply</td>
<td>265.00</td>
<td>5.65</td>
<td>199.7</td>
<td>114.92</td>
<td>8.39</td>
<td>79.8</td>
</tr>
<tr>
<td>Formwork supply</td>
<td>3.00</td>
<td>3.94</td>
<td>1.58</td>
<td>0.91</td>
<td>0.07</td>
<td>0.6</td>
</tr>
<tr>
<td>Steel rebar supply</td>
<td>93.00</td>
<td>3.94</td>
<td>48.88</td>
<td>28.13</td>
<td>2.05</td>
<td>19.5</td>
</tr>
</tbody>
</table>

Figure 3. Estimation of material transport distances with Infraworks 2023 software.
Finally, the calculation of the emissions of the construction stage was based on the estimates of emissions generated by the use of electrical energy and fuels used in the construction processes, where secondary energy became primary energy, obtaining the following results (see Table 4).

<table>
<thead>
<tr>
<th>Items / Resources</th>
<th>Amount</th>
<th>Unit</th>
<th>Embedded Energy (GJ)</th>
<th>Total (t CO2eq)</th>
<th>% Emissions incidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material elimination</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backhoe 62 HP</td>
<td>196.00</td>
<td>hm</td>
<td>112.77</td>
<td>8.23</td>
<td>13.5</td>
</tr>
<tr>
<td>Dump truck 15 m3</td>
<td>981.00</td>
<td>hm</td>
<td>564.45</td>
<td>41.20</td>
<td>67.6</td>
</tr>
<tr>
<td>Concrete pouring</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete vibrator</td>
<td>677.28</td>
<td>hm</td>
<td>24.36</td>
<td>1.78</td>
<td>2.9</td>
</tr>
<tr>
<td>Rebar and formwork</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric shear 3.5 HP</td>
<td>1,479.13</td>
<td>hm</td>
<td>53.19</td>
<td>3.88</td>
<td>6.4</td>
</tr>
<tr>
<td>Steel bending machine</td>
<td>1,479.13</td>
<td>hm</td>
<td>53.19</td>
<td>3.88</td>
<td>6.4</td>
</tr>
<tr>
<td>Electric power</td>
<td>3,150.00</td>
<td>kWh</td>
<td>35.91</td>
<td>1.95</td>
<td>3.2</td>
</tr>
</tbody>
</table>

4. Discussion

From the general analysis of the life cycle of the cradle to the gate of the case study project, it was possible to verify that it will generate a total of 955.31 t CO2eq or its equivalent to 305.44 KgCO2eq/m2 of construction, a value that, when found in the average of similar research results from 220 to 420 KgCO2eq/m2 [18], allow validating the proposed calculation method.

Likewise, it is important to point out that considered a “cradle to gate” analysis the stage with the greatest impact in the construction occur in the materials supply stage 92.5% (See Figure 4), where the greatest impact is generated by the supply of ready-mix concrete 57.5% and the supply of steel for construction 41.9% because these have a long supply chain that incorporates impacts from the exploitation of raw materials, transportation for manufacturing and his own process of manufacturing, so sustainable design should focus on the selection of eco-sustainable materials.
The impact of the transportation stage represents only 1.1% of the total impact and the construction stage generates 6.3% of the impact, evidencing that earthworks generate 81.1% of the impact of this stage, which is why efforts must be made to optimize the productivity of the equipment in order to reduce the carbon footprint in this stage.

5. Conclusions

From the study of the state of the art, it was possible to show that in order to implement adequate sustainability practices in the construction sector, a comprehensive and detailed analysis of GHG emissions or impacts that occur throughout the life cycle of an infrastructure, given that only this type of evaluation will allow us to accurately identify the stages and activities with the greatest impact, as evidenced in the case study where it was verified that the material manufacturing stage represents 92.5% of GHG emissions, so improvement efforts should focus on this stage.

Likewise, it was evidenced that there is currently a wide variety of methodologies and standards for the quantification of GHG emissions, but the most recognized framework for its exhaustiveness and level of detail is the Life Cycle Analysis, however when applied to the construction sector, it presents a limitation in information management, so its integration with Building Information Modeling (BIM) technology is recommended.

Regarding the proposed case study, it was possible to identify that the highest incidence of GHG emissions occurs in the stage of manufacturing and supply of ready-mix concrete materials and reinforcing steel, due to the fact that these materials have an extensive supply chain, where impacts are added from the stage of extraction, transportation and manufacturing of the raw material, so a sustainable design must seek to reduce the use of this type of materials, seek alternative materials and/or seek to optimize manufacturing processes.

Recommend expanding this study, evaluating the proposed methodology in different types of construction projects such as earthworks, construction of road and industrial infrastructure in order to assess how the type of project, site conditions and technology used impact carbon emissions.

Autor Contributions: Conceptualization, methodology, formal analysis, investigation, writing—original draft preparation and project administration, Roberto-Carlos Acero-Condori; software, resources, data curation, editing, visualization and writing—review and supervision, Mauricio-Javier León-Tejada.

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Conflicts of Interest: The authors declare no conflict of interest.
References


The impacts of occupant behaviour on energy performance, thermal comfort, indoor air quality, and health in social housing

Abstract: The UK’s largely inefficient housing is a significant contributor to greenhouse gas emissions and a contributing factor to poor health outcomes of its residents. The social housing stock built between WWII and the 1980’s is the same with a number of high-profile cases related to significant health impacts. It is largely accepted that user behaviour can have a significant contributory factor to these factors. Focusing on a single “flagship” sheltered housing block in East London the aim of this research is to understand and identify post-occupancy user behaviours that affect indoor air quality, thermal comfort, and energy usage, with the purpose of recommending retrofitting strategies. A questionnaire survey was conducted with the occupants to collect data on their behaviour patterns, preference and experiences related to energy use, ventilation and any associated health symptoms that they attributed to their living environment. Preliminary results show that to achieve thermal comfort and the healthiest environment residents must engage with behaviours that are both thermally inefficient and high energy consuming. Further analysis is required to make suitable recommendations, but these could include the installation of mechanical ventilation or providing low energy alternatives for acceptable IAQ. Any change to the building fabric must be accompanied by an education, reward, and support scheme to meaningfully change behaviour. By considering the user behaviour of occupants, retrofit measures can be more effective in reducing carbon emissions whilst also maintaining health environments for residents.

Keywords
Indoor air quality; thermal comfort; building energy performance; energy efficiency; energy retrofitting; occupant behaviour, health and wellbeing.

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1. Introduction

Social Housing in the UK is provided through a mixture of Local Authority and Housing Association owned stock, with the vast majority built between the end of WWII and the early 1980’s (Shelter, 2023). Much of this housing stock (built before energy efficiency and long-term sustainability was central to housing policy and regulation and architectural ethos) is inefficient by modern standards with poor energy performance. In August 2007, the UK Government introduced Energy Performance Certificates (EPC) in England & Wales. An EPC informs you of how energy efficient a building is, how much it’ll cost to heat & light the building, and what its carbon emissions may be. The EPC will give the property an overall rating from A (very efficient) to G (very in-efficient) (EnergySavingTrust, 2022). Only 40% of UK homes in England & Wales meet an EPC rating of A-C, (OpenPropertyGroup, 2023).

There is significant anecdotal and researched evidence that suggests a strong correlation between poor energy performance in residential homes and the ill health of the occupants (International Energy Agency, 2017). Respiratory conditions such as asthma and hay fever can be affected by poor internal air quality (IAQ) in homes and living in an energy inefficient environment can be detrimental to both the physical and mental health of occupants (Wouter Poortinga, 2018). The potential lethal effects of poor housing conditions have been brought to the public conscious recently due to the tragic death of Awaab Ishak, the 2-year-old who died from exposure to mold in his home (Weaver, 2022). The home was provided and managed by Rochdale Boroughwide Housing; a Housing Association who were found by the regulator to be negligible with a litany of failings in the case. They were found to have shown poor overall management and investigation of such issues and ultimately failed at providing a healthy and adequate accommodation for residents across their portfolio (Regulator of Social Housing, 2022).

In addition to the potentially serious impact on the health of its occupants, the energy efficiency of a home has significant ramifications for the environment and the climate crisis we are facing. Central to the UK Government achieving its net zero carbon target by 2050 is to improve the energy efficiency of buildings, with the built environment currently accounting for 25% of greenhouse gas emissions in the UK (UK Green Building Council, 2021; Karlsson, 2021). This highlights the importance of the operational efficiency of building in achieving the carbon reduction targets by 2050 as set out by the UK government (HM Government, 2021).

Whilst newer buildings are designed to embrace environmental sustainability and energy efficiency, existing housing stock is largely inefficient making up circa 48% of emissions of the total built environment (UK Green Building Council, 2021). With much of the social housing stock across both Local Authorities and Housing Associations built prior to modern regulations and policy on energy efficiency standards, comprehensive retrofitting strategies will be required to tackle the scale of the problem in the UK and achieve government targets.

The current cost of living, climate and energy crises increase the gravity and impact of energy inefficiency and its impact on people and environment. The impact of the covid-19 pandemic alongside record increases in temperature saw several days of extremely uncomfortable weather in thermally inefficient homes. The current socio-political situation in Europe has seen gas supplies reduce by 35% and a significant rise in energy costs. (BBC News, 2022). These circumstances have left millions of families facing rising food and energy costs, with some having to choose between ‘Eating & Heating’ (Viner, 2023).

The UK government does not have an agreed published retrofitting strategy, the ambitions to reduce the carbon output of the built environment are contained within the Net Zero Strategy and the Heating and Buildings strategy which focuses on the more immediate need for action to decarbonise heating sources for buildings in the UK setting out an action plan with schemes and policy focus for the 2020’s (HM Government, 2021). Whilst there is not a centralized pot of funding focused purely on retrofitting of housing stock these ambitious targets and plans are underpinned by a few key
accelerator programmes, such as the current Social Housing Decarbonisation fund, the Green Homes Grant, and the most recent Sustainable Warmth Competition.

Newham Councils planned retrofit for the Hamara Ghar sheltered housing scheme is partly funded as part of an award from the Social Housing Decarbonisation fund for homes with an EPC rating of below C. The aim of the fund is to support projects to: reduce carbon emissions; improve fuel poverty and improve the comfort, health and well-being of social housing tenants (HM Government, 2022) in addition to other ambitions. Within this wider national context, The London Councils Retrofit London Housing Action Plan was developed in response to the growing awareness of the urgent need to address the energy inefficiency of the city’s housing stock if the targets as set out by the net zero strategy are to be met. A lack of coordinated national strategy and funding is highlighted with the funding and policy outlined above, described as narrow in its focus and not far reaching enough (London Councils, 2021). The action plan was developed by London Councils, an organization that represents the 32 boroughs and the City of London, in collaboration with a range of stakeholders including industry, government and community groups. Crucially as well as recognising the environmental impacts of our current housing stock. The plan highlights the need to address fuel poverty and improve the health and wellbeing of residents which is exacerbated by inefficient homes and the need for a “whole house approach” (London Councils, 2021).

In the context of occupant behaviour, the plan recognises that the behaviours can have a significant impact on energy use and emissions. To address this, the plan includes measures such as providing education and advice to occupants on how to reduce energy use, and offering incentives for behaviour change, such as lower utility bills for those who adopt energy-saving practices (London Councils, 2021). The plan also includes initiatives to improve the monitoring and feedback of energy use in homes, which can help occupants better understand their energy consumption and make informed decisions about how to reduce it. There is an understanding of the importance of engaging with occupants and promoting behaviour changes as key components of achieving its energy efficiency goals across the city’s housing stock, with a focus on collaboration and innovation across the local authorities and with key stakeholders from the energy, environment, housing and construction sectors. Occupant behaviour is an essential component for any approach to retrofitting and decarbonisation both in terms of implementation and policy, though the specific needs of the end users as per demographic indicators are not always central to government objectives.

1.1 Health outcomes and living environment

The link between living conditions and health outcomes is well known and borne out by many years of research. In terms of Thermal Comfort (TC), there is a known link regarding TC and effects on occupants, in particular more vulnerable groups such as elderly, those with long term conditions such as Chronic Obstructive Pulmonary Disease (COPD), and children (Ormandy, 2012). Both overheating and thermally inefficient homes can have significant detrimental effects on health and can exacerbate or cause long term conditions with both factors being equally important when addressing retrofitting strategy.

The World Health Organisation (WHO) study “Housing, Energy and Thermal Comfort: A review of 10 countries within the WHO European Region” provides an overview of the state of housing and its impact on energy consumption and thermal comfort. The report highlights the prevalence of poor-quality housing and inadequate heating, which can lead to health problems and increased energy consumption (World Health Organisation Regional Office for Europe, 2007). It also examines the factors that contribute to poor thermal comfort, such as inadequate insulation and ventilation. Overall, the report emphasizes the importance of thermal comfort when working towards sustainable and energy-efficient housing to improve living conditions and reduce carbon emissions. Particularly prevalent to the user cohort and project that this study is focused on, is the strategic approach of placing thermal discomfort at the center of retrofit strategy when considering the needs of occupants in fuel poverty. In cases where the thermal comfort and economic conditions of the occupants have not been considered then building retrofitting does not always achieve the expected energy savings and
carbon reduction targets (Vilches, 2017). Occupant’s thermal comfort as a self reporting measure is of particular importance when addressing retrofitting strategies. This is most relevant for those who are facing fuel poverty.

Another well researched area regarding occupant impact is the connection between Indoor Air Quality (IAQ) and health outcomes. With over 4 million deaths per year linked to it, poor indoor air quality can cause a range of health problems including respiratory problems, allergies, asthma, and even more serious illnesses such as lung cancer (Raju S, 2020). IAQ can be affected by a variety of factors, including ventilation, humidity, temperature, and the presence of pollutants such as chemicals, dust, and mold (Tran, 2020). These factors can all have an impact on the quality of the air that we breathe indoors and can lead to a range of health problems. There have been numerous studies investigating this link with the connection between occupant behaviour and indoor air quality long established.

The “Sick Building Syndrome” study conducted by the World Health Organization (WHO) in the 1980’s was a landmark study that investigated the relationship between indoor air quality and the health of occupants. The study aimed to identify the causes of the symptoms that were reported by occupants of certain buildings, which included headaches, fatigue, and respiratory issues (World Health Organisation, 1984). The study found that poor indoor air quality was a major contributor to these symptoms, leading to what became known as “sick building syndrome.” The study highlighted several factors that could contribute, including inadequate ventilation, contamination from outdoor pollutants, and indoor sources such as carpets and furnishings. The study identified the importance of occupant behaviours, such as smoking, the use of cleaning chemicals, cooking and not ensuring adequate ventilation. (Health and Safety Executive, 1993).

The converse relationship between indoor air quality and energy efficiency solutions has also been explored with standards for energy efficiency reducing a lack of natural ventilation and subsequently the indoor air quality. (Liva Asere, 2018) This in turn requires mechanical ventilation which increases energy consumption with the net gain or loss an important factor to be considered in any retrofit plans. In addition, any occupant behaviour that contributed to poor indoor air quality as described would be exacerbated by poor natural ventilation.

1.2 Energy Performance and occupant behaviour

The Energy Performance of Buildings Directive is a European Union directive aimed at the reduction of carbon produced by buildings. Core to the delivery of the directive is the requirement for the energy performance of all buildings to be measured and recorded via an Energy Performance Certificate EPC, which in the UK gives buildings a rating of A the most efficient to G the least efficient. EPC certificates consider the fabric, heating systems, age, insulation and particular fittings such as showers to give the associated efficiency rating for the property (Y. Li, 2019) but do not evaluate user behaviour. Energy performance of buildings is acutely affected by occupant behaviour with a number of studies indicating a significant difference between predicted building performance and measured output (Far, 2022) as much as 300% in some cases (Delzendeh, 2017).

Despite the strong correlation between poor performance, occupant usage and subsequent negative health outcomes, many retrofit strategies do not consider this behaviour due to the variance in behaviour and potential scenarios that could affect performance through usage. Occupant behaviour is core and should be measured via a variety of techniques, ranging from self-reported findings to measuring temperature and moisture of the air within the dwelling (Santamouris, 2005).

Energy consumption, according to The International Energy Agency (IEA) is determined by 6 factors: 1) Climate; 2) Building envelope characteristics; 3) Building services and energy systems characteristics; 4) Building operation and maintenance; 5) Indoor environmental quality provided; and 6) Occupant activities & behaviour (Bruna Faitão Balvedi, 2018).

“Energy related Occupant behaviour… (is defined as) …observable actions or reactions of a person in response to external or internal stimuli, or actions and reactions of a person to adapt to ambient environmental conditions” (Bruna Faitão Balvedi, 2018). Occupants’ decisions and behaviour depend on both deterministic and random responses to stimuli and are thus stochastic in nature; the same
occupant can respond differently, on different occasions and even in response to identical stimuli (Jessen Page, 2007). For example, a home without insulation in the winter months will be far colder indoors than a home with insulation. The occupant residing in said building without insulation would most likely utilize a heater to stay warm inside depending on their individual thermal comfort. Using a heater would increase the energy consumption which will increase the energy bill for the occupant. Alternatively, the occupant could wear additional layers of clothes to combat the indoor temperature instead of using a heater. (Yan, 2015) This decision would not increase the energy consumption and the occupant would not have increased their energy bill.

Because of the complex nature and variance of occupant behaviours a mixture of both users reported finding and technology led monitoring should be utilized to best understand this variance and give accuracy. Stochastic models should account for a variety of behaviours, variation over time, and variation between individuals so that we can achieve more robust renovation and design solutions, better load profiles for sizing and control of energy conversion systems and supply networks and for better energy use and comfort predictions (Juan Mahecha Zambrano, 2021).

2. Methodology

A mixed method including critical literature review and questionnaire surveys were used to understand specific elements of user behaviour and the impact of this on the living environment and health of the occupants. This is within the context of a population of older residents and an older and assumed more environmentally inefficient building. The questionnaire was designed to guide the user to give specific answers that can be compared and analyzed to understand trends against behaviour, rather than subjective user experience.

The first section of the questionnaire focuses on specific elements of occupant behaviour, that could have effects on the indoor air quality of the residence, the heat retention and or loss as well as moisture levels including frequency of opening windows, cooking, washing, clothes washing and drying; utilization of heating and mechanical ventilation and their primary reasons for this. The second section of the questionnaire focuses on any environmental issues internally and externally, such as damp, mold, water leaks and any surrounding pollution. The third section of the questionnaire asks residents about any long-term conditions such as asthma and hay fever, behaviours including smoking and pet ownership as well as any symptoms they suffer from with their associated frequency that could be because of their living environment and IAQ. The symptoms surveyed have been chosen due to their link with poor IAQ. The final questions focus on demographics, occupancy numbers and provide an opportunity for any additional information. All collected user feedback has been fully anonymised with results based on data trends.

Within the earlier stated context of the demographic profile of the residents it was required to work directly with responses allowing them to share their experiences whilst giving quantifiable data points. The study focuses on a total of 26 properties (22% of total households) within the building with the majority being single occupancy and non-working age adults. Whilst the relatively small sample size means that caution has been exercised in drawing conclusions the demographic similarity of the residents has allowed for any results that deviate to be reviewed and analyzed for correlation and patterns to offer suggested reasons as to the potential impact of human behaviour of the reported outcomes. Statistical analysis has been used with a focus on participant demographics, participant behaviour, participant health, participant behaviour in context of reported issues with the building and assessment of reported health symptoms in context of long-term conditions and participant behaviour. There were some void answers throughout the survey i.e., left blank with percentages based on the number of complete answers.

The chosen resident block for this study is an over 50’s only retirement home and sheltered housing unit (Figure 1). The block allows for mixed family households though is aimed at more elderly residents. Of our respondents none were households with any occupants under 18. Excluding void responses 75% of our respondents lived in single occupancy households with 22% of them currently
under occupying i.e., living in 2/3-bedroom properties. 62.5% of respondents were female, 37.5% male. Residency length ranges from 6 months to 29 Years with a median of 10 years. Each resident unit operates on two electric meters with the local authority providing free electricity in the evenings. Though this was not a question asked within the questionnaire survey this was anecdotally feedback via the engagement with residents with feedback that whilst they either do or are encouraged to keep their heating on at night to take advantage of this it often leads to overheating and need to open windows.

![Figure 1. Case study Building.](image)

### 3. Results

#### 3.1 External ventilation

Participants were asked about frequency of window opening across the 4 main living areas; living room; bedroom; bathroom and kitchen during winter and summer to see if behaviour changed depending on season (Figure 2). 65% of respondents opened their bedroom and living room windows at least once a day even in winter suggesting that this is where the most time is spent. 80% of them open their windows less than once a day with 50% not opening their windows at all in their kitchen in winter and 88% never opening their bathroom windows in winter. As expected, participants' use of windows for natural ventilation increases significantly in summer with bedroom and living room windows opened at least once a day by 96% of residents. Similarly, this increased for both kitchen and bathroom windows though not as significantly with 42% of respondents opening their kitchen windows 2-3 times per week and 62.5% of residents still not opening their bathroom window at all even during summer. The primary reason for opening windows across all room categories in winter and summer seasons was to “provide fresh air”. This ranged from 86% to 80% across the bedroom and kitchen which were the primary rooms where windows were opened regularly.
3.2 Cooking, Washing and Heating

As confirmed in a study by Vardoulakis et al. (2020), “Household characteristics and occupant activities play a large role in indoor exposure” to air pollutants. As well as affecting IAQ, these activities are known to play a significant role in the thermal regulation and carbon pollution caused by a building and so an understanding of these behaviours is key to any retrofitting strategies. As per figure 3 and 4, 35% of residents wash and cook once a day with the associated indoor air pollutants and heat creation from this. This is against the reported natural ventilation that only 22% of respondents open their bathroom windows in winter and 50% open their kitchen windows. In terms of mechanical ventilation this increases to 58% using extractor fans in their kitchen at least 2-3 times per week with 33% still not using any mechanical ventilation. In the bathroom where 88% of respondents do not open their windows at all in winter 62% use mechanical ventilation at least once a day with 37.5% not using any mechanical ventilation. Despite this only 15% residents have reported any damp or mold in their bathroom. Of this 75% do not use any mechanical or natural ventilation at all, which given known causes for damp and mold in property is likely to be connected. The building has communal washing and drying facilities with 62% of residents from our sample using this as their primary facility to wash and dry clothes. Clothes drying is known to increase moisture within the room environment however of the 31% that use an airer within the property there is only once case of damp or mold reported with the resident not opening their windows in the winter or using mechanical ventilation (they do regularly open external windows in the summer months).
3.3 Health Conditions and symptoms

Smoking is known to have a particularly negative affect on IAQ and health both through direct and passive intake of inhalants. Only 3.89% of residents are smokers as per the survey with no reported respiratory or other health symptoms as well as regular external ventilation practices associated. With such a small, reported sample of smokers any conclusions cannot be drawn as to impact on IAQ.

As noted above the survey asked respondents about their long-term conditions and any related or unrelated health symptoms focusing on both conditions and symptoms linked to IAQ and occupant behaviour. As per fig 6, 5% of occupants have asthma, 3% hay fever and 1% suffer from both. Of those with Asthma 40% reported damp or mould in their property and account for 50% of total reported cases of damp and moulds from all respondents. Despite the low reported prevalence of known issues within the properties i.e., damp and mould and the low rate of residents suffering from either hay fever or asthma there were significant reported health symptoms, itchy or watery eyes at 56%, headache at 52% and lethargy or tiredness at 44% (see Figure 5).
At 56% itchy or watery eyes is the most prevalent health symptom despite only 14% of those reporting this have hay fever (Figure 6). Looking at other potential irritants 64% of this cohort cook at least “once a day” with 42% cooking from “2-3+ times a day”. Looking at just this subset of 64% of those with itchy or watery eyes 55% never open their windows during winter and all spend 18-24 hours a day inside the property. Though this is for the winter months, it is possible that this constant exposure to indoor pollutants is a cause for the reported symptom. Similarly, looking at the 56% who report headaches, 76% cook at least once a day and 60% of them do not open their kitchen windows in winter. Again, all spend 18-24 hours a day in their homes. Though a direct cause and effect cannot be drawn due to other potential lifestyle factors a statistically significant correlation can be seen within our sample size. Whilst 44% of residents report lethargy or tiredness, no statistical significance is prevalent though it could be proposed that the age of the respondents is a potential factor.

4. Conclusions

This study examining occupant behaviour via the survey questionnaire has revealed some interesting correlations between external ventilation and poor health outcomes. The study aimed to investigate the relationship between occupant behaviour in relation to daily living habits, use of external and mechanical ventilation, heating use and health outcomes among occupants in an over 50’s retirement sheltered housing building. The findings of the study indicated some correlations between the rate of ventilation and health. The analysis suggested that inadequate ventilation coupled with regular cooking was associated with an increased risk of symptoms associated with IAQ particularly itchy and watery eyes and headaches. These findings align with existing literature, emphasizing the importance of proper ventilation for maintaining acceptable indoor air quality and occupant well-being. A more expansive assessment of all residents in the building with follow up interviews about behaviour and health outcomes should be considered to enhance the findings as well as a direct comparison of data measuring devices (IAQ data loggers) against each respondents’ responses as well as a refinement of questions asked. Retrofitting strategies could be considered to address the insufficient ventilation reported especially during the winter months and in key areas of heat, moisture and pollutant creation such as the kitchen and the bathroom. The suggested retrofit strategies must be assessed in context of wider factors such as budget and impact of interventions on residents, thermal comfort and energy performances.
Acknowledgments: This research is funded by the Newham Council and University of East London. The research team would like to thank all the staff and residents who supported this study.

References


30. Weaver, C., 2022. Awaab Ishak’s death shed light on a social housing scandal. Now we have a brief
    chance to fix it. [Online] Available at: https://www.theguardian.com/commentisfree/2022/nov/23/awaab


    Comfort; A review of 10 countries within the WHO European Region, Copenhagen : World Health
    Organisation Regional Office for Europe.

    impacts of energy performance investments in low-income areas: a mixed-methods approach. Public
    Health Research, Volume No 6.5.

    future improvement. Renewable and Sustainable Energy Reviews, Volume 113.

    264-268.
Modular design and manufacturing processes using space-filling solids.

This study examines the feasibility of employing space-filling solids in architectural-scale designs and explores the application of digital design methods in digital architecture. Specifically, the comparison and analysis focus on two nature-inspired space-filling solids, namely cubes and truncated octahedrons. The truncated octahedron exhibits favorable flexibility and adaptability when combined with modular design principles. Digital architecture relies on the advancement of digital tools, encompassing digital software and digital machines. Notably, 3D printing possesses exceptional shaping capabilities, offering expanded possibilities for constructing digital architecture.

To investigate digital architectural processes, two experimental case studies are conducted. The first case study involves the design of the 'Flowing apartment,' which employs deformed cubes generated through laser cutting and 3D printing techniques. The second case study features the 'Nomad POD,' designed utilizing deformed truncated octahedrons and 3D printing technology. By utilizing digital design and processing methods, this research contributes to the understanding of digital architectural practices and their connection to digital manufacturing. The integration of space-filling solids, digital design, and 3D printing enables innovative approaches to architectural design and construction. This paper provides insights into the potential applications and benefits of utilizing space-filling solids at an architectural scale, highlighting their role in fostering modularity and facilitating the realization of intricate architectural designs.

Keywords
Space-filling solids, digital architecture, digital design, digital manufacturing, 3D printing.

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1. Introduction

The escalating demands of urbanization and population growth have resulted in the scarcity and escalating value of land within megacities. (United Nations Human Settlements Programme, 2020) As the price of land continues to rise, its proportion relative to the total property price increases, necessitating innovative approaches to optimize space utilization in buildings while maintaining affordability. Nature provides a valuable source of inspiration in this regard. To address the challenge of space optimization, the concept of "Mind the gap" (GRIFFITHS, 2012) has emerged, aiming to develop a system that utilizes underutilized areas within cities to expand their capacity. Space-filling solids, such as cubes and truncated octahedrons, offer geometrically suited solutions for filling urban voids, gaps in the urban fabric, and leftover spaces between existing buildings. (Scott, 2011) These solids exhibit structural integrity, enabling their integration into modular design frameworks. By deploying a standardized structure frame, the city’s expansion can mimic cellular growth, providing a cohesive structural foundation while facilitating the redefinition of interior and exterior spaces. (Zanni, 2021) The advent of digital design methodologies has opened up new possibilities in architecture, empowering architects with algorithmic, parametric, and nonlinear thinking capabilities, among other advanced tools. (Claypool, 2021) These digital design processes yield visual outcomes that often surpass the limits of imagination. (Bridle, 2023) Furthermore, the seamless integration of digital design with manufacturing processes enhances the potential of digital architecture. (Zixu Liu, 2022) Techniques such as 3D printing, laser cutting, and robotic manufacturing augment production efficiency and accuracy, offering avenues for mass customization. (Berry, 2000) Although the current maturity of these technologies within the architectural field remains limited, their widespread adoption is imminent. (Salvador, 2006)

Vitruvius, an ancient Roman architect, advocated for three fundamental qualities—Venustas (beauty), utilitas (utility/functionality), and firmitas (strength/durability)—in architectural design. (Moragan, 1914) While Vitruvius’s principles of beauty have withstood the test of time, the evolution of technology, economics, culture, policy, and population has influenced architects’ values and aesthetic perspectives. (Olivier, 2021) Each architectural style, including those stemming from previous industrial revolutions, boasts distinctive characteristics. In the era of the fourth industrial revolution, characterized by digital advancements, architectural designs have embraced a more technological and futuristic outlook through the widespread adoption of digital design and manufacturing technologies. (Fengwei, 2021) Digital technology not only transforms production processes but also shapes aesthetic perceptions. The utilization of digital manufacturing technologies, coupled with the mature use of digital design tools, has spawned a new aesthetic paradigm in digital architecture. (Lin-Lin Chen, 2012) However, it is important to note that the current costs associated with digital manufacturing equipment still exceed those of traditional methods. Nevertheless, the expanding array of options for fabricating non-standard, intricate components offsets these costs. Moreover, with increasing demand, digital mass production in factories can effectively reduce costs while maintaining stringent quality standards. Consequently, the cost differential between a doubly curved façade and a traditional planar wall becomes inconsequential. (Berry, 2000)

This paper endeavors to explore the intersection of space-filling solids, digital design methodologies, and manufacturing processes within the realm of architectural design. By investigating the potential of modular design and digital tools, our research aims to contribute to a comprehensive understanding of the evolving field of digital architecture and its implications for optimizing space utilization in urban environments. (Fbricate, 2011) The integration of computation in architecture began with the advent of computer-aided design (CAD) in the early 1980s, which has now become a standard practice in architectural and engineering offices. In the 1990s, further advancements were made in computer programming and animation software, enabling architects and designers to realize complex architectural design ideas and explore design methods. This period witnessed the emergence of parametric design, algorithmic design, data-driven design, and non-linear design concepts. (Harding, 2012) Parametric design involves expressing design parameters and rules through algorithmic thinking, establishing the relationship between design intent and design response. Parametric
modeling software, such as Rhino, Maya, and 3ds Max, enables designers to link models to parameters and modify the shape of the model by adjusting these parameters. (Stavric, 2011) This approach facilitates the rapid exploration of various design schemes, suitable for both irregular and complex shapes in traditional and exploratory design contexts. Many pioneering architects and designers have successfully adopted parametric design methods in their work. Algorithmic design employs algorithm program editors to assist in the design process. (Gursel Dino, 2012) It involves following a set of rules or algorithms, particularly with the aid of computers, to solve design problems. Different scripting languages, such as Rhino script, Python, MEL, and Grasshopper, are utilized within specific design software to manipulate code and generate visual outcomes. Algorithmic design harnesses the computational capabilities of computers, allowing for self-optimization and inspiring designers with unexpected yet controllable results. It is particularly useful for tackling criteria-driven and non-standard design tasks. (António Leitão, 2011)

Parametric design and algorithmic design are distinct approaches, but they often intersect in practice. Designers frequently combine these methods to optimize shapes, alternating between parameter adjustments and algorithmic transformations to achieve the desired design outcomes. Both parameterization and algorithms serve as containers of values, providing designers with the flexibility to adjust code and parameters to achieve different results. Design forms resulting from the combination of parametric and algorithmic design are commonly referred to as Pragmaticism. (Romero, 2021)

Computer-aided architecture design (CAAD) encompasses computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies, forming a comprehensive repository of building records employed by architects and architectural companies. The realization of physical entities through CAAD involves three steps. First, designers create 2D or 3D models using digital design software and export them in a format compatible with digital manufacturing software. Next, they process the files using CAM software, configuring parameters for machine operation based on the chosen manufacturing method. Finally, digital manufacturing equipment, such as CNC machines, 3D printers, laser cutters, or robots, is employed to process the materials and fabricate the physical entities. This process seamlessly connects digital design, digital processing, and digital construction, providing precise manufacturing of complex components. Furthermore, the visualization aspect ensures that the digital representation accurately reflects the final physical output. (António Leitão, 2011) (Claypool, 2021)

Effective collaboration between professional designers, construction parties, material suppliers, and subcontractors is crucial for successful projects. Traditional communication methods often fall short in addressing the complexities of modern construction, necessitating digital architecture designers to collaborate with other professionals throughout the design and construction phases. Building Information Modeling (BIM) platforms serve as digital communication hubs for project information. Popular BIM software such as Revit by Autodesk and Digital Project by Gerry Technology, based on the CATIA modeling engine, facilitate collaboration, and allow the importation of digital models from other software. Collaborative design enabled by BIM not only enhances efficiency and convenience but also makes large and complex projects feasible. The continuous collaboration between various teams on the BIM platform brings the project closer to reality, thereby assisting in post-construction activities such as management, operation, and demolition.


2.1 Space-filling solids as a design element

Space-filling solids in design explores the concept of utilizing space-filling solids as a design element. The chapter begins by drawing inspiration from nature, where various examples of space-filling patterns can be found. One such example is the hexagonal honeycomb created by bees, which optimizes space utilization without gaps. Darwin’s research suggests that bees chose the hexagonal shape because it allows them to store more honey while using less material compared to square or
triangular cells. Another natural example is foam, which consists of trapped gas pockets within a liquid or solid structure. Water foams, in particular, demonstrate a flexible and multi-scale system where bubble walls meet at plateau borders. The walls form stable connections, meeting at angles of 120 degrees, and can rapidly rearrange into threefold junctions, when necessary. Additionally, migratory birds offer insight into combining different shapes to reduce wind resistance during flight. The dynamic and flexible connections between individual birds within a migration group result in the creation of various shapes.

Moving into two-dimensional space, tessellation becomes a key consideration for filling a plane with identical, equal-sided, and equal-angled cells. The three options available are triangles, squares, and hexagons (Figures 1, 2, and 3). However, without the constraints of equal-sided and equal-angled cells, an array of geometric shapes can be used to create visually appealing tiles, carpets, and mosaics. Expanding to three-dimensional space, space-filling solids, or space-filling polyhedral, demonstrate elegance in industrial production and architecture. Five primary space-filling convex polyhedra are identified: the cube, triangular prism, hexagonal prism, truncated octahedron, and gyrobiastigium (Figure 4). The cube, with its six square faces, represents the only Platonic solid possessing this property. Other examples include the uniform triangular prism, the hexagonal prism with equal hexagonal bases, and the truncated octahedron with its fourteen faces comprising regular hexagons and squares.
Deforming space-filling solids introduces new possibilities for design. Cuboids, characterized by horizontal floors, vertical walls, and 90-degree corners, offer flexibility in altering space. By adjusting the lengths of the cuboid’s edges, the overall space can be transformed while still maintaining its fallibility (Figures 5 and 6). The combination of space-filling solids, such as the hexagonal prism, allows for increased options in spatial organization (Figures 7 and 8). The truncated octahedron, when positioned with a hexagonal face as the base, offers larger horizontal areas and enhances the overall design (Figures 9 and 10). By considering the geometry and employing vertical division, innovative combinations and structures can be achieved while preserving the essence of the original shape.

Figure 5. Deformed cube frame structure system.
Figure 6. People eye of a complex building.
Figure 7. Deformed hexagonal prism frame structure system.
Figure 8. People eye of a complex building.

Figure 9. The combination among the three types of floors.
Figure 10. Deformed truncated octahedron frame structure system and people eye of a complex building.
2.2 Algorithmic design development.

Table 1. Six loops of a typical group for filling up space.

<table>
<thead>
<tr>
<th>Loops Directions</th>
<th>Loop 1 (black)</th>
<th>Loop 2 (Green)</th>
<th>Loop 3 (pink)</th>
<th>Loop 4 (blue)</th>
<th>Loop 5 (yellow)</th>
<th>Loop 6 (grey)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>+0</td>
<td>+4.899</td>
<td>+9.798</td>
<td>+14.697</td>
<td>+19.596</td>
<td>+24.495</td>
</tr>
<tr>
<td>Y</td>
<td>+0</td>
<td>+8.485</td>
<td>+0</td>
<td>+8.485</td>
<td>+0</td>
<td>+8.485</td>
</tr>
</tbody>
</table>

With the assistance of coding, designers can automate the generation of various combinations using space-filling solids. The Maya Embedded Language (MEL) is a scripting language utilized in Maya, a 3D Graphics Software, to simplify tasks. Although the process is automated, the conceptualization and work still belong to the designer. To enable the truncated octahedron POD to grow automatically, the designer needs to determine the lengths of the three dimensions in the X, Y, and Z directions. After calculating the 3D model, the dimensions are found to be 29.393877, 16.970562, and 10.5, respectively. Combination and repetition play crucial roles in the automation process. While a cube requires a simple loop, the truncated octahedron necessitates six loops (see Table 1 and Figure 11).

![Figure 11. A typical group.](image)

Understanding the aggregation method allows for the completion of over half of the program. Here is an example of one loop within the complete script (As Below) Similar to the above loop, there are five more loops with different parameters. By adjusting these values, diverse architectural forms can be generated (see Figure 12-13). Altering the maximum number of replicates in each direction controls the maximum number of objects generated in each loop. From an architectural perspective, designers can manipulate the size of the site by adjusting the building boundaries and density.

```pascal
float $dx = 4.899; // Define the dimension in the X direction
float $dy = 8.485; // Define the dimension in the Y direction
float $dz = 3.464; // Define the dimension in the Z direction
string $sel [] = `ls -sl`;  // Select an object and store its position
for ($x = 0; $x < 5; $x++) {  // Define the threshold for x
    for ($y = 0; $y < 5; $y++) {  // Define the threshold for y
        for ($z = 0; $z < 5; $z++) {  // Define the threshold for z
            $comp = `duplicate $sel[0]`;  // Duplicate the object
            move -r ($x * 29.393877) ($y * 16.970562) ($z * 10.5) $comp; // Move the duplicated object to the specified location
            refresh;
        }
    }
}
```
Architecture driven by data is an emerging approach to design. In today’s digital world, our online activities and information are continuously collected. Platforms like Google Trends analyze vast amounts of user search data to identify various trends (see Figure 14). For instance, it reveals that people prefer renting studios over one-bedroom or two-bedroom flats, with less demand for the latter. Such data-driven insights can inform the design of residential buildings and cater to the demand for different types of housing. As we gather data from natural sources (such as sun, wind, water) and artificial sources (such as commercial buildings, residential buildings, roads, stations, bridges), we can establish different parameters and constraints. Building regulations can also be considered as guiding data for automated design. In this exercise, random data is used to represent unknown constraints, providing an intriguing demonstration of data-driven architecture design. A random number is employed as a condition for duplicating the truncated octahedron POD. If the conditions are met, the POD is duplicated and moved to a specified location. The following is the core loop of the entire script:

```plaintext
float $dx = 4.899;  // Define the dimension in the X direction
float $dy = 8.485;  // Define the dimension in the Y direction
float $dz = 3.464;  // Define the dimension in the Z direction
int $amount = 2;    // Set an integer
int $max1 = 2;      // Set an integer
int $max2 = 2;      // Set an integer
int $max3 = 12;     // Set an integer
string $sel[] = `ls -sl`;  // Select an object and store its position

for ($x = 0; $x < $max1; $x++) {    // Define the threshold for x
    for ($y = 0; $y < $max2; $y++) {  // Define the threshold for y
        for ($z = 0; $z < $max3; $z++) {  // Define the threshold for z
            int $rand = rand($x + $y + $z);  // Define the threshold for the random number
            if ($rand % $amount == 1) {  // Set a condition for the random number
                $comp = `duplicate $sel[0]`;  // Duplicate the object if the random number meets the condition
                move -r ($x * 29.393877) ($y * 16.970562) ($z * 10.5) $comp;  // Move the duplicated object to the specified location
                refresh;
            } else {  // Do not duplicate the object if the random number does not meet the condition
                continue;
            }
        }
    }
}
```
2.3 Free design tool for POD design

There is a wide range of digital design methods available in architecture, each suited to different conceptual requirements. When considering the concept of the "Nomad POD," it becomes evident that buildings need to adapt to the various life stages of their occupants. Different life stages entail different demands for living spaces. In alignment with the standard POD, which is based on a deformed truncated octahedral shape, several variations of PODs have been designed to serve different functions. The frame structure POD serves as the foundational element, providing structural integrity. By adding a slab onto the frame, shared facilities, open spaces, or green areas can be created. Further additions of walls and roofs result in inhabitable spaces. These different POD configurations, including the frame POD, panel POD, and six room module PODs, offer discrete combinations to cater to specific stages of human life. (Figure 16)
Through the use of architectural terminology and design principles, the Nomad POD concept demonstrates the versatility and adaptability of buildings to meet the evolving needs of their occupants. The variations in POD configurations provide opportunities for flexible and functional spatial arrangements, allowing for efficient use of space and the optimization of living environments.

3. Results

3.1 Prototyping through digital fabrication

Digital manufacturing, including the use of 3D printing technology, has gained significant traction as a versatile and efficient method of construction. By leveraging digital design and computer-aided manufacturing (CAM), digital manufacturing processes have become more streamlined and effective. While off-site manufacturing remains prevalent, allowing for modular component production in
factories and subsequent on-site assembly, there are also on-site digital manufacturing applications for smaller-scale buildings. The distinct advantage of 3D printing lies in its ability to shape complex, three-dimensional forms with precision. Unlike traditional construction methods that often rely on fitting irregular components using standardized elements, 3D printing enables direct fabrication without the need for alterations. This ensures that the final product closely aligns with the original design, preserving the aesthetic integrity of the architectural space. In the case of the "Nomad POD" concept, the frame structure system assumes a crucial role. (Figure 17) illustrates non-standard beam and joint components that present challenges when employing traditional construction techniques. However, 3D printing offers a solution by maintaining design accuracy without compromising architectural aesthetics. The outer layer, composed of fireproof plastic, is 3D printed, while the inner layer consists of reinforced concrete. The 3D printed plastic serves as a mold for the concrete, eliminating the need for additional decorative finishes. This approach allows for customization, enabling the printing of varying plastic thicknesses to meet insulation specifications and incorporating insulation material between double-shell plastic layers. Such optimization reduces material waste and ensures the distribution of structural forces in an efficient and dynamic manner.

While large-scale on-site 3D printing of concrete is being explored, limitations in printer size and working radius often necessitate off-site component manufacturing and subsequent on-site assembly. Two methods can be employed: pre-casting plastic and concrete components off-site and assembling them on-site, or printing plastic off-site, assembling plastic molds on-site, and pouring concrete into these molds. Each approach offers advantages, such as increased production control and reduced transportation costs. To showcase the potential of 3D printing in digital manufacturing, two models were created using standard FDM 3D printing: a 1:20 scale representation of a standard frame POD and a 1:2 scale component model. These models demonstrate the feasibility and effectiveness of 3D printing for architectural applications, highlighting its role in enhancing the construction process.

3.1.1 3D printing 1:20 scale model (prototyping)

The frame POD, as a typical example, consists of various components, including four types of joints and seven types of beams, totaling 66 parts (Table 2). Given the 1:20 scale of the model, the components are relatively small and do not contain concrete fillings. In practice, steel joints are incorporated into the components for convenient assembly. A 2mm diameter steel bar is employed as the connecting element (Figure 19). To streamline the assembly process, each component is marked with unique identifiers during production, facilitating efficient and accurate assembly (Figure 18).

The assembled 1:20 model, divided into three floors, demonstrates the flexibility of the design (Figure 19). Through digital manufacturing techniques, the transition from digital design to production is expedited, increasing the likelihood of transforming design concepts into tangible structures. The modular production in factories has benefited from enhanced precision and quality. The 3D printer, as a pivotal digital manufacturing tool, can either print the entire object in one go or fabricate modular parts for subsequent assembly. In either case, the overall structure's shape remains intact and unaffected. The utilization of digital manufacturing equipment not only saves time but also improves the feasibility of materializing architectural designs. Factory-based modular production ensures high precision, while 3D printing enables the creation of intricate components with ease. By bridging the gap between digital design and physical construction, digital manufacturing presents a powerful avenue for realizing architectural visions.
Due to time and budget limitations, a portion of one joint from the overall frame POD was selected for the 1:2 scale model (Figure 20). The dimensions of this model are 92mm, 127mm, and 237mm, respectively. The Ultimaker-3 printer was utilized for this project, which offers printable dimensions of 197mm, 215mm, and 200mm (Ultimaker-3 website). Since the component exceeded the printer’s size capacity, it was divided into four parts using Luban software, a CAM tool that automatically subdivides large components and generates connectors (Figure 20).
After completing the digital model, the file was imported into Ultimaker Cura software to set the 3D printing parameters, such as print speed, temperature, and layer height. This step allowed for model inspection, identification of any issues, and estimation of printing time and material requirements (Table 3). Instead of fireproof plastic, white PLA, and transparent PLA with a diameter of 2.85mm were used for the experimental printing.

<table>
<thead>
<tr>
<th>Component</th>
<th>Time</th>
<th>Material weight</th>
<th>Material length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part 1</td>
<td>4h 37min</td>
<td>221g</td>
<td>28m</td>
</tr>
<tr>
<td>Part 2</td>
<td>3h 29min</td>
<td>201g</td>
<td>26m</td>
</tr>
<tr>
<td>Part 3</td>
<td>1h 52min</td>
<td>213g</td>
<td>27m</td>
</tr>
<tr>
<td>Part 4</td>
<td>1h 41min</td>
<td>225g</td>
<td>29m</td>
</tr>
<tr>
<td>Total</td>
<td>5h 39min</td>
<td>860g</td>
<td>110m</td>
</tr>
</tbody>
</table>

Table 3. Information table for each component.

During the printing process, the support materials were also printed layer by layer to ensure structural stability (Figure 21). The four printed parts were subsequently assembled (Figure 21, 22). While the entire building is supported by reinforced concrete, the plastic shell serves to shape the continuous surface and contribute to the building’s aesthetic appeal. In this case, the internal shape of the component was redesigned to align with the distribution of forces, allowing for material savings, ease of transportation, and installation. Concrete was poured into the plastic mold to complete the component (Figure 22). The combination of digital manufacturing techniques and concrete pouring enables the realization of complex architectural designs with enhanced efficiency and accuracy.

4. Discussion

The discussion surrounding digital design and manufacturing in architecture highlights both the immense possibilities and the current challenges in this field. The "Nomad POD" project serves as a prime example, showcasing the flexibility and creative potential of digital design, particularly through the utilization of space-filling solids. The integration of big data analysis further enhances the scientific and intelligent aspects of architectural design. However, it is crucial to acknowledge that digital design is still a nascent discipline, and there is much room for growth and development. Digital manufacturing, a vital component of this process, brings automation and efficiency to construction practices. 3D printing technology, in particular, offers the advantage of producing intricate and precise shapes without relying on traditional fitting techniques. Yet, challenges arise when translating these advancements to real-scale construction. Limitations such as the size of 3D printers, structural stability, and material strength present obstacles that need to be addressed for widespread implementation. Presently, 3D printing is primarily employed for constructing wall components, while other architectural elements still rely on conventional construction methods. However, modular 3D printing conducted off-site emerges as a promising solution. This approach enables the fabrication of complex non-standard components and addresses the construction of large irregular surfaces. By combining the precision of digital manufacturing with the efficiency of modular construction, this method has the potential to revolutionize the architectural industry. In conclusion, digital design and manufacturing have opened up new horizons for architectural exploration. While substantial progress has been made,
ongoing advancements and innovative solutions are necessary to overcome existing challenges. By embracing these opportunities and pushing the boundaries of technology, the integration of digital design and manufacturing can reshape the future of architecture, offering groundbreaking possibilities for construction practices.

5. Conclusions

In conclusion, this research has explored the implications of digital design and digital manufacturing in the field of architecture. The study has demonstrated that a variety of digital design methods can generate multiple outcomes in a short timeframe, leveraging the design potential of computers and offering new avenues of inspiration. Algorithmic design, artificial intelligence, and big data analysis have emerged as prominent trends, shaping the future of digital design. Space-filling solids have been identified as a significant element in digital design, facilitating architectural diversity and enabling the exploration of modular architecture solutions. The use of deformed geometries derived from these solids presents opportunities for innovative room configurations. Furthermore, 3D printing technology has revolutionized digital manufacturing by allowing the production of non-standard complex shapes through the printing of modular components. This advancement has eliminated the need for traditional fitting techniques, enhancing efficiency and precision in the manufacturing process. Through the analysis of two experimental case studies, the research has provided a comprehensive overview of the digital design, processing, and manufacturing procedures. The findings highlight the flexibility, efficiency, and seamless integration of these processes. While digital design and manufacturing offer immense potential, it is important to acknowledge that the subjective nature of aesthetics and the complexity of architectural design continue to require human expertise and intervention. This research contributes to the academic discourse on digital design and manufacturing in architecture, providing insights and references for further exploration and development in this field.

Bibliography


Customized Mass Production in Modular Design Approach for Lightweight Structures Using Bent Metal Pipes.

This research paper explores the potential and practical applications of automation in the field of robotic construction, with a focus on metal pipe bending. The study investigates the use of automated robots as supplementary team members in construction projects, aiming to achieve NetZero construction by reducing on-site manufacturing and emphasizing on-site assembly for improved efficiency and safety. The integration of 3D printing technology into key structural components is also examined to address complex construction challenges.

In the modern era, the development of automated and robotic construction systems is essential for achieving competitive, market-driven, and rational building practices. These systems encompass various stages of the construction process, including the manufacturing of building materials, prefabrication of construction components, on-site construction, facility management, rehabilitation, and recycling. By leveraging automation and robotics, construction projects can achieve accelerated design and construction phases, high-quality standards, and cost-effectiveness.

Flexible automation, supported by computer-assisted planning, engineering, and construction management techniques, offers solutions to overcome challenges in the construction industry. The implementation of automated and robotic construction technology can effectively address the increasing demand for building projects, especially in regions with high labor costs. Automation has the potential to reduce the labor cost share by 40% or more, leading to increased productivity and year-round operation. Moreover, the adoption of robotic technology in construction enhances working conditions, promotes better health and safety standards, and requires advanced mechatronics knowledge and skills.

By optimizing construction processes through automation, shorter construction periods can be achieved, resulting in faster real estate availability and improved returns on investment. The integration of automation and robotics in construction is crucial for the rationalization of the industry and holds great potential for enhancing productivity, cost-efficiency, and overall project outcomes.

Keywords
automation, robotic construction, metal pipe bending, 3D printing, NetZero construction, efficiency, safety, productivity, cost-effectiveness.

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1. Introduction

The concept of off-site construction, deeply rooted in architectural history, has emerged as a transformative solution to housing and non-domestic construction challenges. From the innovative practices of ancient Rome, where pre-fabricated components were meticulously crafted off-site (Redshift, 2021), to the industrial revolution's impact on construction techniques, this approach has continuously evolved. However, it was during the tumultuous period of World War II that off-site construction methods, (Ovando Vacarezza, 2014) particularly modular construction, experienced a momentous breakthrough. The pressing need for expedited housing construction in the aftermath of the war prompted the widespread adoption of modular techniques. Entire housing units were fabricated in controlled factory environments, introducing standardization, reduced construction timelines, and cost efficiencies. Although modular building has grown in popularity in recent years, it is not a wholly innovative method. Prefabricated homes were brought from New York to California during the 1849 California Gold Rush. (Wilson, 2019). The concept of flexible structures can be traced back to the early 20th century with the emergence of architectural movements like De Stijl and Constructivism. These movements emphasized adaptability and flexibility in design and construction. In the 1960s and 1970s, architectural experiments with modular and adaptable structures, such as the Metabolism movement in Japan, showcased the potential of flexible architecture. (Hilde Heynen, 2002) (JENCKS, 1997) This significant historic juncture exemplifies the profound impact of off-site construction in addressing critical societal needs. Today, propelled by technological advancements, including digital design tools, robotics, and automation, off-site construction continues to redefine the architectural landscape. By embracing innovation and fostering continuous improvement in the construction industry, the full potential of off-site construction can be unlocked, transcending the limitations of traditional on-site methodologies.

In the realm of architecture and construction, an enduring challenge of the past was the customization and intricacy of building components. Traditional methods often imposed limitations on the creation of unique architectural features, and bespoke elements demanded significant time, expense, and skilled craftsmanship. (Pye Tait, 2008) However, the advent of digital manufacturing and 3D printing technologies has ushered in a transformative solution to this age-old predicament. Architects and designers now harness the power of computer-aided design (CAD) software to conceive intricate digital models, seamlessly translating them into precise instructions for the 3D printing process. (Menna Hazem, 2007) (Jovanovic, 2013) (Paritala, 2017) (Peter s. p. Wong, 2017) By employing these technologies in off-site mass manufacturing, the production of complex components and modules with customized features becomes a reality. (Boychenko, 2017) The integration of digital manufacturing and 3D printing not only enables architectural boundaries to be pushed, but also yields cost and time efficiencies. Automated precision reduces waste and human error, streamlining production processes and lowering material costs. Furthermore, fabricating components off-site and transporting them to the construction site significantly expedites on-site construction while minimizing disruptions. This remarkable advancement addresses historical challenges, underscoring the transformative potential of digital manufacturing and 3D printing in the construction industry. (JANE BURRY, 2020) However, in 2019 COVID-19 pandemic had a huge global impact, notably on the building industry. Short-term production, supply capacity, and worldwide growth were reduced, resulting in economic issues. In the long run, however, the pandemic has spurred the use of digital technologies, resulting in greater cooperation, improved value chain management, and data-driven decision-making processes such as Digital Twins. (United Nations Environment Programme,
2022) (Murray, 2023). There has also been an increase in expenditure in standardizing building rules for safety and sustainability. In addition, the sector is focusing more on industrialization, utilizing modularization, off-site production automation, and on-site assembly automation to boost efficiency and productivity. These themes represent the industry’s reaction to the pandemic’s issues, as well as the need for resilience, sustainability, and technical innovation. (Cheng Zhuo, 2023) The main advantage of offsite building over traditional construction is assumed to be reduced construction time on site, along with higher quality, a more uniform result, and less snagging and defeasibility. (Goodier, 2023) (Harrison, 2023)

This research paper explores the enduring legacy of off-site construction and its potential for shaping a sustainable and efficient built environment. It analyzes the current need for mass production in off site construction, emphasizing the concept of growing architecture to fit the surrounding environment and the design requirements. The paper also investigates the use of 3D printing for joints and highlights the reuse of metal pipes to reduce waste and promote comprehensive material utilization. By delving into these topics, the paper aims to contribute to the understanding and advancement of off-site construction in terms of mass production, adaptability, 3D printing, and sustainable practices.

2. Design & Construction Methods

This research paper is based on customization of modular structures using bent pipes and 3d printed joints for design of the train station. To develop the project team focused on methods such as leveraging the specific benefits of analogue and digital fabrication. Methodology also includes several tests around physical model development and then transition to digital model. Techniques, such as 3d printing joint with PLA material using Cura software to slice the model from Rhino in meshes, and reusing of rubber pipes are employed for the test experiments and form finding processes. This iterative approach is represented in the research in a way of learning aspects from an analogue model and then implementing them and changing the digital one. After the first attempt with simple cross sectioned nodes and pipes the team understood the limitations of this specific node. Going back to the digital model, a new set of 3d joint were developed, and new module combinations achieved.

The utilized methodology also includes parametric design strategy using Rhino 7, which has built in Subdivision tools. It allowed the team to reach the digital pipes utilizing Pipe command applied on curves, which represent the structure of the modular train station. The command MultiPipe has been utilized in the project to make 3d joints in the points, where pipes were connecting to each other or to the ground. Digital analyzing tools in Rhino 7 and Scan&Solve plugin helped to compare the behavior of the straight pipe and bent one after applying pressure of 5000 Pa.

Customized modular design involves creating a structure composed of individual modules that can be tailored to specific requirements. This approach offers flexibility, adaptability, and ease of assembly. By allowing customization of modules, architects can meet unique design challenges and create structures that respond effectively to external factors and human needs. Parametric design techniques enable the establishment of rules or parameters that define the geometry and behavior of modules and joints. This approach facilitates efficient customization and variation within the design framework. Architects utilize parametric design to generate and sift through countless design possibilities based on multidimensional aspects. Computational approaches have proven to boost design efficiency by exploring the potential of modular approaches in architecture.

Various digital design tools, such as computer-aided design (CAD) software, are instrumental in creating and manipulating 3D models of the structure, modules, and joints. These tools enable precise design iterations, visualization, and analysis. By leveraging digital design tools, architects can enhance the efficiency and accuracy of the design process, leading to improved outcomes in customized modular architecture. Bent metal pipes serve as the main structural components in customized modular designs. These pipes are typically made of lightweight and high-strength materials such as
materials such as aluminum or steel alloys. The use of these materials ensures structural integrity while minimizing weight, resulting in efficient and resilient structures. Structure flexibility is usually a component of the core conversation when discussing modularity and other adaptability features, which implies that the core discussion section must be flexible to be consistent with adaptable architecture. We used NODES, which are the most economical and sustainable options, to debate this in our design process.

The joints connecting the bent metal pipes are produced using 3D printing technology. Specifically, 3D printed metal joints offer design flexibility, rapid prototyping, and precise customization capabilities. Metal powders and suitable 3D printing processes, such as selective laser melting (SLM) or electron beam melting (EBM), are utilized to create these joints. The use of 3D printing technology enables architects to achieve intricate designs and tailor joints to specific project requirements.

By melting the work piece and adding filler material, welding is a method of joining separate pieces. It is also described as a method of consistently attaching metal components using heat. To create a 3D metal item, 3D welding is characterized as building up metal beads layer by layer. By adopting the welding procedure, it is more affordable and productive to make metal products in large quantities.

Ren et al. research has focused on 3D repairing technology, where surface patching has significantly increased accuracy, efficiency, and dependability of component fixing, in addition to producing new 3D objects.

Pipe and tube bending can be done in a variety of ways. The size of the pipe or tube to be bent, the wall thickness, the required radius, and, of course, the material must all be considered. Then there is the equipment and procedures in hand, as well as the machine operator's abilities. A broad range of bends may be created with high precision and attractiveness using a clever combination of material, machines, processes, and experienced operators. The use of a "rotary draw bender" is the most current way of bending pipes and tubes. Round pipe, as well as round, square, and rectangular tubing, is clamped into a form and pulled to the necessary radius over a die. Each die must fit the outer dimensions of the material being bent as well as the required radius. However, once set up, the process can swiftly create high-quality parts. The radii can be as small as half the pipe's diameter.

3. Results

Based on methodology, the team developed the following experiments and achieved following results.

3.1 Physical Experiments

The form-finding process was conducted in two steps to explore different possibilities and overcome limitations:

The first step involved creating a simple cross connection as a basic configuration for the module (Figure 1). This initial configuration allowed for experimentation and analysis. However, during this stage, it was discovered that the simple cross connection had limitations in terms of the distance it could cover. This limitation prompted further exploration to enhance the module's capabilities. To overcome the limitations identified in the first step, additional connections were designed. These connections had two to four outlets for connecting pipes, enabling the module to cover larger areas, such as train stations. In train station projects, it is essential to minimize the number of columns and supports to ensure the safety and ease of communication for passengers on platforms (Figure 1).
3.2 Digital Model development

3.2.1. Transition to Digital Model and Customized Mass Production

As the form-finding process using 3D printed joints and reused rubber tubes yielded valuable results, the research then progressed to the next step: transitioning to a digital model. This transition allowed for increased precision and efficiency in the iterative design process. Moreover, it supported the concept of customized mass production, which is crucial in achieving faster results and a variety of outcomes (Figure 2).

Rhino, a powerful computer-aided design (CAD) software, was utilized in this research to create the digital model. With Rhino, the design team could work with curves and orient them in both 2D and 3D space. This flexibility enabled them to experiment and play with different design configurations, generating numerous varieties of outcomes for exploration. The process involved manipulating the curves and adjusting their parameters to create a wide range of module shapes and configurations. By leveraging the digital tools provided by Rhino, the design team could quickly iterate and evaluate the visual and structural aspects of each variation. Working with curves in the digital model allowed for precise control over the geometry and dimensions of the modules. The design team could easily adjust the curvature, angles, and intersections, fine-tuning the overall aesthetics and functionality of the customized modular architecture. Through this iterative process, the design team could test different design possibilities, exploring the potential of the module in various contexts. They could simulate the module’s behavior in
different environments and assess its performance under different loads and constraints. This digital experimentation provided valuable insights and feedback, guiding the refinement of the design.

The use of Rhino as a digital design tool not only facilitated the exploration of design variations but also enabled efficient customization. By parameterizing the design, the team could easily modify and adapt the modules to specific requirements, such as space constraints and functional needs. This customization capability is a key aspect of the customized mass production approach, allowing for efficient production and assembly processes while maintaining design consistency (Figure 3).

**Figure 3.** Digital model of the structure applied on the functional diagrammatic arrangement of the functional organization for the train station.

### 3.3 Stress Analysis

As the next step in the process of delivering the project some stress analysis has been done using Rhino 7 and SnS Pro Evaluation plugin. The pressure of 5000 Pa was applied to both the steel straight and bent pipes diameter of 400mm (figure 4). This pressure represents the load exerted on the pipes during the analysis. The stress analysis provided statistical data on the structural response of the pipes under the applied pressure. This data includes information such as maximum stress values, deformation, and factors of safety, which are important for assessing the structural integrity and performance of the pipes (figure 4). The results of the stress analysis were interpreted and evaluated to determine whether the pipes can withstand the applied pressure without exceeding their structural limits. This step helps in assessing the safety and reliability of the pipes in real-world applications.
Material Summary (linear pipe)

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Description</td>
<td>Steel, Stainless (ferritic)</td>
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<tr>
<td>Density</td>
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<td>Default Failure Criterion</td>
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<tr>
<td>Tensile Yield Strength</td>
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Material Summary (curved pipe)

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Component Geometry Summary (linear pipe)

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Component Geometry Summary (curved pipe)

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Results: (linear pipe)

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<tr>
<td>Y-Displacement</td>
<td>-1.9512E-003 mm</td>
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<tr>
<td>Z-Displacement</td>
<td>-1.9367E-003 mm</td>
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Results: (Curved pipe)

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<td>Y-Displacement</td>
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<td>Z-Displacement</td>
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<tr>
<td>Total Displacement</td>
<td>4.5905E-019 mm</td>
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</table>

Figure 4. Digital image of preliminary stress analysis and results of displacement on a linear pipe (A, B, C) and curved pipe (D, E, F). Tables are showing the data for respective components and their geometry.
3.4 Components

For the manufacturing strategy, a 1:25 scale model was created using a combination of 3D printing and precise pipe bending techniques. The joints of the model were 3D printed using high-density PLA (Polylactic Acid) filament, chosen for its strength and durability. Rhino 7, a 3D modeling software, was utilized for developing the model, with the subdivision tool employed to refine the detailed geometry. To generate the pipes, the multi pipe command in Rhino was used, enabling the automated creation of pipe structures from specified curves. For the 1:25 scale model, copper pipes with a diameter of 15mm were utilized and carefully bent to match the required angles and curves. This ensured accurate alignment and fit during the assembly process. The combination of 3D printed joints and precisely bent copper pipes allowed for customization and precise fitting, enhancing the overall structural integrity of the module. These manufacturing techniques, coupled with digital modeling and advanced software tools, aimed to expedite construction compared to traditional methods.

![Image of 3D printed components](image1)

**Figure 5.** The component requirement for one module a) the different radii for pipe bending b) the joints required for assembling of one module c) The joint and pipe connection detail.

3.5 Transition from digital model back to physical

3.2.1. 3d joints

In this research paper, the team presents a comprehensive and detailed guide to the 3D printing process utilizing PLA filament, accompanied by widely utilized slicer software applications Cura. There are specific requirements and steps listed to achieve the willing result. The model
should be watertight or solid, avoiding double surfaces and intersections. It must be clear what is the interior and what is the exterior. In Rhinoceros there is a tool to check it out: ShowEdges. This tool can show any Naked and Non-manifold edges. Those are usually a big issue for 3D printing as the way a computer reads these files may not be as they are designed. By default, Rhinoceros does not allow the creation of non-manifold edges. The model should be in the right scale and in millimeters. The physical prototype model has been designed in scale 1:25.

- Exporting modeled joints in right scale your file from your program of choice as an STL (mesh and save as Binary if prompted).
- Importing the model into Cura slicer software.
- Selecting the appropriate printer profile for compatibility. In the case of this project the team used Ultimaker S5 printer with Fast profile template for using Left Extruder with PLA material.
- Orienting the model to optimize print quality and adhesion.
- Choose print quality settings such as layer height (0.2mm) and infill density 50% and structure – gyroid.
- Generate the G-code by clicking “Slice”. Right after slicing the model software provides printing time and the weight of used material. For the joints team approached for the project, time varies between 4-7 hours per one joint. To optimize printing time of 23 joint required by the project team used 3 printers and arranged several nodes at one printing bed.
- Save the G-code file to an SD card or transfer it to the 3D printer.
- Load PLA filament and heat the printer bed to the recommended temperature.
- Start the print job and monitor the process for any issues.
- Adjust settings or troubleshoot if necessary.
- Allow the printed object to cool before removing it from the print bed.
- Remove support structures if applicable.

3.6 Bent Pipes

Once the team developed a digital model of the train station module, is it possible to make precise curvature of the pipes. The team simulated the automated process using an analogue approach, employing a rotary bender to develop structural elements from copper pipes with a 15mm diameter at a 1:25 scale. Each pipe schedule had a specified wall thickness, and although there was a tolerance, a small variation in wall thickness was possible. This variation needed to be considered, especially when using precise tooling for bending with short radii. To account for this difference, the team carefully took into consideration the tolerances during the bending procedures. The exact and snug fitting tooling was utilized to achieve the desired bends while accommodating any potential variations in the wall thickness. The pipes were marked at equal intervals of 25 mm, ensuring a linear curvature by keeping them on a straight line to avoid double curvature and keeping the marks in template. Figure 6. Using a mobile manual pipe bender securely fixed to a vice, the team followed the marked points while bending the pipe. This approach allowed for precise bending while accounting for potential variations in wall thickness, ensuring accuracy and quality in the final structural elements.
3.7 Assembling the model using KIT

Figure 6. Analog pipe bender and using a segmental making to bend pipe to template and individual radius.

Figure 7. Assembly process of the 1:25 model the is representing one module of the train station. Images includes (from top to right) 3D printed joints, bended copper pipes, detail of the assembled joint, assembly process and after assembly and erected model.
A combination of digital and analogue approaches was used during the assembling process. The pipes were put in their assigned placements, with continual reference to the structure’s 3D model. The 3D model gave explicit assembly instructions, directing the proper positioning of each pipe. These meticulously organized pipes were then coupled with their 3D printed joints, which were allocated specified spatial places inside the building model. The inherent flexibility and tension of the pipes became apparent as the assembly continued. This stress in the pipes contributed to the model’s self-sufficiency, giving stability and structural integrity. The interaction of the digital representation and the physical assembly enabled a seamless translation of the design idea into a concrete architectural form.

3.8 Environmental and Construction strategy applied for the train station project

To implement the reduction of sources, materials, and waste while construction and demolishing teams approached circular economy as a key aspect of the project. Instead of a permanent design project presents a flexible structure which can change, grow, and shrink. Using recycled steel as a structural element will speed up the project by eliminating the need to wait for the material to be produced. However, to use these recycled materials, they must undergo chemical and thermal treatment to purify the metal and guarantee long-term durability.

To achieve sustainability in the project the team proposes offsite modular manufacturing, which includes repairing existing pipes in the workshop. Thermal - the steel pipe is heated to a feverish temperature. This will remove contaminants from the steel as well as rust from the surface. Chemical – Zinc (zinc chloride) is a chemical that protects the outer surface of steel from rust. The following step is to bend pipes with automated rotary pressure applied by a robotic arm. Simultaneously nodes and connections are being printed using the direct metal laser sintering (DMLS), which utilizes lasers. By layer-wise solidifying metal powder layers in areas of the layer matching to the cross-section of the three-dimensional component in the appropriate layer, complex parts can be created directly from 3D-CAD models. Once all elements are ready, they are delivered to the building site. Assembling process is realized and controlled by robots. Having a digital twin of the physical outcome, robots manipulate with a pick and place approach. The next step is to spray all necessary treatments for the structure, such as fire treatment and anti-corrosion.

Thinking about long-term use of the train station, the team had in mind that the population of the town is growing, and the station should be able to provide service for bigger amounts of passengers. Structure of the train station can be changed by using the same construction technology - robotic manipulated and controlled. Some parts can be oriented in a different way, some of them can be reused in another project, some of them which can’t be used anymore can go back to the workshop to be treated and/or recycled.

Figure 8. (A). Life cycle of the project and econometric diagram of the train station, (B) components of train station.
3.8.1. Net-Zero structure

- **Sustainability**
  - By reusing pipes, the demand for new raw materials is reduced, minimizing the environmental impact associated with metal extraction, processing, and manufacturing. This approach promotes resource conservation and contributes to a more sustainable construction approach.

- **Reduced Waste**
  - Reusing pipes eliminates the disposal of old or unused pipes, thereby reducing construction waste. This waste reduction strategy helps minimize the amount of waste sent to landfills and aligns with the principles of a circular economy, where materials are kept in use for as long as possible.

- **Design Consistency**
  - Reusing pipes ensures design consistency and maintains a unified aesthetic throughout the structure. This is particularly relevant in architectural projects such as train stations, where architectural coherence and visual harmony are essential considerations.

- **Growing Buildings and Surrounding Adaptability**
  - The concept of growing or adaptable buildings refers to structures that can accommodate future expansions or changes in use. Research can explore the feasibility and implementation of off-site construction approaches, including the use of metal pipes, for creating flexible and adaptable buildings that can easily accommodate modifications or expansions over time.

- **Improved Construction Efficiency**
  - Studies consistently demonstrate that off-site construction can significantly improve construction efficiency, reduce project duration, and enhance on-site safety. Researchers have employed methodologies such as case studies, simulations, and data analysis to evaluate and quantify these efficiency gains.

- **Quality Control and Standardization**
  - The literature emphasizes that off-site construction allows for greater control over quality assurance through standardized manufacturing processes and controlled environments. Researchers have used quality assessment tools, inspections, and comparative studies to evaluate the quality performance of off-site construction compared to traditional on-site methods.

- **Cost Analysis**
  - Cost considerations have been a focal point in many studies. Findings indicate that while off-site construction can require higher upfront investment, it offers potential cost savings in terms of labor, material waste reduction, and schedule compression. Researchers have employed life cycle cost analysis, cost modeling, and comparative studies to assess the economic viability of off-site construction.
  - Repurposing and adapting existing pipes instead of purchasing new ones significantly reduces material costs in construction projects. This cost-saving measure allows for efficient allocation of resources and maximizes the budget for other aspects of the project.
4. Conclusion

In conclusion, this study presents an architect’s perspective on the utilization of customized mass production and modular design principles in the development of lightweight structures using bent metal pipes. By incorporating cutting-edge technologies such as 3D printing, digital modeling, and precise pipe bending techniques, the project demonstrates the immense potential of off-site manufacturing and on-site assembly processes. The seamless integration of digital tools and analog methods during the assembly phase enabled architects to precisely arrange the pipes according to the 3D model, ensuring accuracy and spatial coordination. The inherent flexibility and tension observed in the pipes further enhanced the structural stability and self-supporting nature of the final assembly, showcasing the architectural prowess in utilizing materials effectively. Furthermore, this research underscores the architectural community’s response to the challenges presented by the COVID-19 pandemic. The incorporation of digital tools has not only facilitated improved collaboration and data driven decision-making processes but has also empowered architects to exercise greater control over the construction value chain. Additionally, the emphasis on standardized building codes for safety and sustainability, coupled with the exploration of industrialization through modularization and automation, highlights the commitment to advancing the field. By successfully implementing this project, architects are poised to contribute to the creation of sustainable, efficient, and adaptable buildings that address the evolving needs of society.

Moving forward, continued research and development will play a crucial role in refining processes and pushing the boundaries of architectural innovation in the construction industry. Specifically, it addresses the pressing challenge of modular architecture. By utilizing digital design and fabrication tools, this approach enables the creation of structures that are both flexible and durable. This advancement in design has far-reaching implications for the construction industry, as it opens new possibilities for creating efficient and adaptable buildings. This research provides a new perspective on sustainability by promoting the adoption and reuse of existing structures instead of constructing new ones. This approach significantly reduces costs and minimizes the resources associated with the process of demolishing and rebuilding. By embracing the principles of adaptive reuse, this innovative design and construction methodology contributes to the preservation of resources and the reduction of environmental impact. It offers a more efficient and sustainable solution to the ongoing challenges of urban development and construction practices.

However, further research is needed to explore the mechanical properties and long-term performance of 3D printed metal components and to optimize the bending processes for different pipe materials and wall thicknesses. The results and findings of this study demonstrate the potential of combining metal 3D printing and precise pipe bending techniques in architectural applications, paving the way for future advancements in the field of customized mass production and modular design in lightweight structures.

References


CHAPTER 4
Environmental Sustainability and Policies
Social sustainability assessment in a sector of high risk of landslides in Arequipa, Peru

Landslide phenomena frequently occur in environmental limits, as is the case of riverside areas, these are due to anthropogenic factors such as cutting operations, dumping of substances, removal of vegetation cover, disorganized growth of the population that leads to construction next to slopes, producing a negative impact on the environment. In addition, the influence of seismic, morphological and climatological factors, added to the anthropogenic factors, make the environment susceptible to the occurrence of slope landslides, being of great importance the understanding of the human perception in these inhabited areas in order to implement unconventional stabilization methods that mean sustainable, efficient, low-cost alternatives and that achieve the expectations of the inhabitants. This research is carried out in the sector of Santa Cruz de Lara, an area consolidated on a slope near to the Socabaya River in Arequipa, which represents a highly vulnerable area to the occurrence of landslides, however, it presents a strong rooted population. The identification of latent risks was carried out, in terms of physical factors such as topographic survey, field exploration of the study area, as well as the physical-mechanical characterization of the soils present to understand the nature and behavior of the soil. Social factors were evaluated in the study area, through observation and a 25-question interview, based on the Geo-SAT tool (Geotechnical Sustainability Assessment), which includes the population’s perception of landslide risk. According to the results analyzed, it can be observed that the study area is vulnerable to the incidence of landslides, however, the population has deep social roots in the area and does not consider moving, since they consider the area to be safe. The study highlights promoting policies to improve infrastructure to prevent possible landslides and reduce the vulnerability of the population.

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1. Introduction

Natural disasters due to climate effects are affecting more people and causing economic devastation around the world [1-3]. In Europe, 17 countries, due to natural disasters, have increased inequality between regions, reduced the room for maneuvering public finances and its effects are cross-border [4]. The focus of the cause of disasters is improperly placed on climate change instead of on those who can prevent the damage caused by its effects on nature [5]. Urban expansion in Arequipa has reached the area of the banks of the Socabaya River, which is one of the 10 rivers in the city, with a minimum flow of 0.42 m³/s in the dry season in August, and 79.7 m³/s in the rainy season from December to March (Pearson type III logarithmic distribution for a return period of 50 years), being able to reach a maximum flow of 89.2 m³/s for a return period of 100 years, according to probabilistic models published by the national water authority [6]. In some areas of the hillside on the banks of the Socabaya River, there are houses, mostly informal constructions, without planimetry, of varied structures and foundations. These riparian zones are characterized by being in constant change due to processes of erosion, rain, landslides, movement of water masses, stones, and sedimentation [7]. If human modifications are added to these natural conditions due to disorganized urban expansion with buildings close to slopes, the dumping of substances, cut and fill operations, deposit of materials, and removal of vegetation cover, among others, cause these areas to be more vulnerable to the occurrence of landslides on slopes. Urban expansion is a factor with a great impact on the evolution of cities, both in environmental aspects and in public health, quality of life, and socioeconomic factors such as migration from the high Andean areas to more developed coastal cities [8]. That is why there is informal housing in undeveloped areas at the level of the rest of the city, in areas with low bearing capacity soils or areas near to slopes. Slopes are always subject to instability problems generated by their own evolution dynamics, as is the case of erosive processes that can be caused by the erosive potential of rain, infiltration conditions, surface runoff, topography, soil type, geological and geomorphological characteristics, physical-chemical and mineralogical evolution of the soil, among others processes; when the agent that produces erosion is surface water, gullies are generated which dynamic evolution, associated with the duration and intensity of the rains, can trigger a landslide process and can generate slope failure, dragging everything in its path, situation that may include houses and human lives [9, 10]. Assessing the social sustainability of homes located in areas at high risk of landslide phenomena is crucial to avoid loss of human life and deterioration or total loss of infrastructure, which once occurred, increase poverty rates, make it difficult to access clean water, impede transit, trade and the economic development of the population, increasing social gaps. In developing countries, such as Peru, there is an urgent need to evaluate and prevent this type of phenomenon.

2. Materials and Methods

2.1 Description of the study area

Socabaya is one of the 29 districts of the province of Arequipa, located southwest of the city as shown in Figure 1. Its coordinates are 16° 27’ south latitude and 71° 31’ west longitude, and its altitude is approximately 2,300 m.a.s.l. It has a population of 75,351 inhabitants and a population density of 4042.44 inhabitants/Km².
The study area is divided into two zones: the lower part of Santa Cruz de Lara and Villa Santa Cruz. Both zones are divided by a rural road that runs parallel to the Socabaya River, which functions as a trunk axis, represented by a red line in Figure 2. The Socabaya River is a physical-functional axis of the city’s ecosystem [11], and is the district’s main water resource. Its flow reaches a minimum of 0.42m³/s in the winter months, while in summer it can increase to 79.3/s. [12]. During the summer months, rainfall increases considerably, up to 11.5 mm/day in the summer months [13], added to the wind direction [14], which causes rivers and torrents (runoff streams) to increase their flow, causing a risk factor for landslides. The consolidated buildings in the study area, mostly single-family houses, are related to population growth and the increase in land value [15], causing more and more urban settlements on the slopes of hills, streams, and river banks.

2.2 Physical factors

The physical factors focus on the topographic survey and field exploration of the study area, as well as the physical-mechanical characterization of the soils present to understand the soils’ nature and the slope’s behavior.

2.2.1. Topographic Survey

The frame POD, as a typical example, consists of various components, including four types of joints and seven types of beams, totaling 66 parts (Table 2). Given the 1:20 scale of the model, the components are relatively small and do not contain concrete fillings. In practice, steel joints are incorporated into the components for convenient assembly. A 2mm diameter steel bar is
employed as the connecting element (Figure 19). To streamline the assembly process, each component is marked with unique identifiers during production, facilitating efficient and accurate assembly (Figure 18).

The assembled 1:20 model, divided into three floors, demonstrates the flexibility of the design (Figure 19). Through digital manufacturing techniques, the transition from digital design to production is expedited, increasing the likelihood of transforming design concepts into tangible structures. The modular production in factories has benefited from enhanced precision and quality. The 3D printer, as a pivotal digital manufacturing tool, can either print the entire object in one go or fabricate modular parts for subsequent assembly. In either case, the overall structure’s shape remains intact and unaffected. The utilization of digital manufacturing equipment not only saves time but also improves the feasibility of materializing architectural designs. Factory-based modular production ensures high precision, while 3D printing enables the creation of intricate components with ease. By bridging the gap between digital design and physical construction, digital manufacturing presents a powerful avenue for realizing architectural visions.

2.2.2. Topographic Survey

The topographic survey was carried out to graphically represent the relief of the existing slope on the ground by means of contour lines with an equidistance of 1 m, complemented with cross sections every 20 meters for a better interpretation of the slope and existing natural and artificial elements in the raised area, given that the raised slope is located approximately 200 meters upstream from the Socabaya bridge. For this, in the field data collection phase, we first proceeded with the help of a GPS Navigator receiver to take exit points with their coordinates (North, South, and Height) to start collecting data with the Leica TS07 2" Total Station, as shown in Figure 3, then we proceeded to import the data from the Total Station and processed them for the creation of the plans.

2.2.3 Field exploration

The field exploration was carried out by means of pits, for which 5 pits were excavated in the slope (02 at the top of the slope, 02 in the base, and 01 in the central part) based on the specifications of standard NTP 339.162 (2001). From these pits, altered soil samples were extracted in plastic bags (Mab) and unaltered soil samples in blocks (Mib), according to the specifications of standard E.050.

2.2.4 Physical-mechanical characterization of soils

The physical-mechanical characterization tests, which were performed according to the specifications of the standard NTP, were: Moisture content (NTP 339.127), Liquid limit, plastic limit, and plasticity index (NTP 339.129), Granulometric analysis (NTP 339.128), Classification of soils (NTP 339.134), Relative specific gravity of solid particles (NTP 339.131), In-situ unit weight of soil by the sand cone method (NTP 339.143), Direct shear in soils under drained consolidated conditions (NTP 339.171).

2.3 Social factors

Social factors were evaluated in situ, by observing the area and a 25-question interview, based on the Geo-SAT tool [16], conducted with the population of the study area, between 19 and 65 years of age. For the evaluation of the response scales regarding social factors in general, the Kelders participation scale
was taken as a reference that has been used in similar studies [17]. On this community social rating scale, total response scores ranged from 35 to 62. Those families whose total interview score was ≥40 scored 3, the highest score; those who were between <40 and ≥20 scored 2 and for those who were <20 the score was 1, which implied the lowest score in social factors.

The questions to assess the socioeconomic level of the population include the profession, family composition, which evaluates the family burden and population density (≥8 scores 1, between <8 and ≥4 scores 3 and <4 scores 5), property (own home scores 5, rented home scores 2), time inhabiting the area (≥20 scores 5, between <10 and ≥20 scores 3, <10 scores 1), type of house (wood or other temporary materials, score 1; cemented bricks or stone, self-built, score 2; cemented bricks and self-built foundations, score 3; cemented bricks, with self-built foundations and plans, score 4, cemented bricks, with foundations, flats, with participation of an engineer, scores 5) and the services received (water, drainage, electricity, garbage collection, scores 5, only light scores 2).

Questions to assess social factors include citizen participation in community activities such as sports, neighborhood meetings, cultural events; transparent government of the municipality; the proximity to medical assistance, the perception of security in the area regarding landslides and citizen security; and, the possibility of moving before the occurrence of previous landslides. (Values range from 1 “Harmful, very little, never, very bad” to 5 for “Significant improvement, always, very good”).

2.3.1. Ethical consideration of research

Only those over 18 years of age were interviewed after giving their verbal consent for the interview. The in situ information provided by the interviewees contains authentic and reliable information on the real situation of the study area. The management of bibliographic data and expert judgments will only be used for research and academic purposes. The names do not appear anywhere in the publication.

2.3.2. Sampling procedure

The interviews were carried out between the researchers and a selected group of students, where an introduction was given about the need to know their opinion about the project. The interviews were carried out in a mixed way, presenting open and closed questions in order to know the socio-cultural aspects of the inhabitants of the area. Using Louangrath’s formula [18] to determine the sample size of the houses that are close to the banks of the Socabaya River within the study area, it was calculated as follows:

\[ n = \frac{N}{1 + Ne^2} \]

where,

- \( n \), sample size.
- \( N \), target population (20 households).
- \( e \), acceptable test error (0.05).

A sample (\( n \)) of 20 dwellings was used, that is, all the dwellings were interviewed.

2.4 Sustainability factors

The household survey used had a mix of closed and open-ended questions, based on the Geo-SAT tool [16] used to measure social impact. Data obtained as texts from open-ended questions were coded and entered into the design of experiments as variables to accommodate quantitative analysis. The
surveys were submitted to the judgment of three experts, who validated the instrument. The Geo-SAT tool [16] was proposed to analyze sustainability in geotechnical projects, the purpose is to have a tool that can help make decisions that promote sustainability. For the present research, the social aspect was used based on 31 sub-indicators distributed in 8 stages: community, security, livelihood, resettlement, geo-ethics, political, land use, landscaping and infrastructure. Because it is an analysis of the study area in its current state, the resettlement stage was not considered for this research. These were weighted on a scale from 1 (harmful) to 5 (significant improvement). The total score was calculated, averaged, and presented in a radial polygon plot. The larger the area of the polygon, the more sustainable the project. Thus, the polygons help to understand the project integrally, understanding the value given to the social dimension and thus being able to propose solution measures in future projects.

3. Results

3.1 Physical factors

3.3.1. Topographic Survey

According to the topographic survey, the slope under study is located approximately 200 meters upstream of the Socabaya Bridge. On the slope’s top there is a road with a paved section and another unpaved section that serves as access to the surrounding urban area. At the slope’s foot is the Socabaya river bed. Along the slope is a concrete-lined irrigation channel. The slope elevation, from the foot to the crown, is approximately 22 m. The slope varies between 50% to 70% and the inclination between 26° to 36°.

3.3.2. Field exploration

Two main soil types are found in the zone: one is silty sand with high humidity, medium compactness, firm consistency, weak cementation, and medium density; and the other is silty sand with gravel with low humidity, medium to high compactness, hard consistency, strong cementation, and high density.

Along the slope, there are herbaceous, shrub, and tree species, which predominate from the channel to the slope’s foot and a few at the top of the slope. In addition, minor landslides and major soil erosion processes can be observed. It is known that vegetation cover can produce favorable or unfavorable effects on slope stability; the vegetation protects the soil from climatic effects and roots increase the strength of the soil-root system; thus, deforested surfaces receive greater volumes of precipitated water and are more vulnerable to erosion processes [9]. These factors generate uncertainty in the behavior of the slope and, therefore, in its stability.

3.3.3. Physical-mechanical characterization of soils

According to the tests performed, mainly two types of soils were identified in the area: Soil 1: Silty sand (SM), with 27% fines and a friction angle of 30.4°, reflecting medium strength. Soil 2: Gravelly silty sand (SM), with 13% fines and a friction angle of 36.8°, reflecting high strength.

Both soils are resistant and, therefore, the slope is estimated to be stable. However, the constant erosion processes, to which the slope is subject due to surface water from heavy rains, decrease the mass of the slope and, therefore, decrease its stability, potentially causing slope failure.
3.2 Social factors

According to the observation and interviews conducted in the study area, it was possible to know that, according to the social evaluation scale of the community, an average score of 2.15 was obtained, on a scale of 1 to 5, which means that the social factors are intermediate [19], Figure 4.

![Figure 4. (a) Social factors and (b) Socioeconomic factors, both measured with the Geo-SAT tool.](image)

According to the evaluation of socioeconomic factors, the population has an average score of 3.66 on a scale of 1 to 5, which is an intermediate-high value, also considering that the average family load per dwelling has a value of 3, which is low. The houses are built informally by the owners themselves, most of whom know about construction because they work as masons, with foundations, but without plans and without the intervention of engineers, for economic savings. The level of education is low; most of the workers are blue-collar workers. The population’s perception of risk is low; all of those interviewed think that the area is safe from landslides and river inflows, with an average score of 4 on a scale of 1 to 5, indicating that they are deeply rooted in the area and do not intend to move from their place of residence. In many cases they do not have all the services, only electricity, nor do they have a paved road, only a rural dirt road, they do not have much citizen participation and do not trust the municipal authorities, but most of them live in their own brick houses. The study area (Santa Cruz de Lara and Villa Santa Cruz, in Socabaya) is located on the slope of Cerro Santa Cruz, which is approximately 25 meters high, has an average slope of 100% and is 300 meters long. At the foot of this slope is the Socabaya riverbed, so this region is prone to landslides during the rainy season.

3.3 Geo-SAT Indicators

The Geo-SAT tool was used as part of the social evaluation for geotechnical projects, obtaining Figure 5, considering the 7 stages evaluated:

3.3.1. **Community (2.22 / 5 points):**

- Community consultation: There is no community consultation plan; during the survey, it was identified that activities are carried out without thinking of representing the
population. On the other hand, local community services exist, but they do not provide the most appropriate service.

- Culture: There is no consideration given to public art in the study area, and the cultural and religious identities of the area are not recognized or protected, as the population maintains that these activities are being lost over the years.
- Archaeology and local heritage: The inhabitants do not recognize archaeological elements in the study area, despite the historical importance of the area.
- Intergenerational and gender practices: The study area has a primary focus on the male gender for employment opportunities, however, there is no focus on any age group. In addition, employment opportunities are not related to cultural and religious groups.
- Cohesion: According to the survey, it was evident that there is no integration in the community. In addition, they consider that the government institution worsens the situation of the community, showing that they consider there is a high rate of corruption.

### 3.3.2. Security (2.5 / 5 points):

- Security: structure/facility: The area is considered safe, unnatural activities (terrorism or attacks) do not exist in the area.
- Security: community: Public spaces are not differentiated from private spaces. Public spaces are fenced off and are rarely used.

### 3.3.3. Livelihood (2 / 5 points):

- Livelihood: health and nutrition: There are no habitats that can cause diseases, the public sanitation system is correct, and there is clean water in communities and municipal cleanliness.
- Livelihood: income and employment: Many people have jobs in the study area; there are a large number of people engaged in construction activities, where their work centers are close to their homes. This mass of workers does not have training on awareness in their workplaces.

### 3.3.4. Land use and Landscaping (2 / 5 points):

- Land use: The study area does not present a potential for urbanization, as the site is populated at low density. Land use does not have an effect for future use.

### 3.3.5. Infrastructure (2 / 5 points):

- Infrastructure: electricity: The study area has an electrical system provided by SEDAPAR (Servicio de agua potable y alcantarillado de Arequipa), which is supplied at the regional level.
- Infrastructure: irrigation and water: The water supplied in the study area is adequate; the irrigation system is operated by the municipality.
- Infrastructure: food control: This indicator does not apply to the research.
- Infrastructure: connectivity: The connectivity in the area is correct, it does not present any
inconvenience, nor does it provide opportunities for interaction between communities. On the other hand, the project is not located near a navigable waterway, since the Socabaya River has very little flow during most of the year.

3.3.6. Political (2.33 / 5 points):

- Political domestic: Provincial boundaries are well defined, which means that there are no social conflicts. However, the democracy index does not exist, as it is considered that there is no transparency in management. There are laws at the provincial level that are in force.
- Political international: The study area does not consider international political impacts. The study area is not included in the River Basin Organizations (RBO) Score because the Socabaya River is not identified.

3.3.7. GeoEthics (3 / 5 points):

- GeoEthics: information sharing: The community is not informed about activities that could be carried out in the area. There is a certain rejection of new projects by the villagers.
- GeoEthics: research: The present research project is promoted by the Peruvian government; however, the area of choice is up to the group. There are no projects that promote the study in that specific area.

![Figure 5. Radial graph of Geo-SAT stages. Own elaboration.](image_url)

It is determined that the study area does not correctly comply with the sustainability established by Geo-SAT, because it has an average of 2 out of the 5 possible points to achieve, which means that the study area has a "reduced" impact on the social sustainability of the area.
4. Discussion

The survey based on the geo-SAT tool allowed us to understand to a large extent the social reality of the study area. According to the results analyzed, the population of the study area is very attached to their homes and does not consider moving, as they consider the area to be safe. The inhabitants have socioeconomic capital that includes a job, their own masonry house, and all services (water, sewage, electricity, garbage collection), which gives them the capacity to produce goods for their families. However, it was detected in the survey, their low citizen participation in community activities, they do not assume leadership roles and any other civil participation that builds the social resilience of an individual in the face of emergencies [19, 20]. On the other hand, vulnerability is increased by the lack of emergency response capacity on the part of the government and the remoteness of the medical post that would force them to travel a long distance to access medical services. Mountain regions are vulnerable to climatic hazards [21, 22]. Vulnerability is determined by the nature and severity of the hazard, the sensitivity of the environment, the number of people affected, and the capacity for recovery [19, 23]. In Peru, the frequency of landslides due to the phenomena of "El Niño" are becoming more frequent and devastating due to the activation of ravines called "dry ravines" because they are only activated by heavy rains caused by "El Niño" [24]. According to the social and physical factors, it can be observed that the study area is vulnerable to the incidence of landslides induced by climate change and associated with erosion processes.

Among the observations made in the development of the evaluation with the Geo – SAT tool, it was found that several sub-indicators do not apply to the study area; this is understood because the tool was used in Pakistan, having a different social reality than the one analyzed in this paper. In addition, it applies more to geotechnical projects that have already been executed and not so much to the planning stage.

5. Conclusions

It can be concluded from this social sustainability assessment study that the population does not perceive danger in the study area; however, there is a high susceptibility to landslides due to the type of soil, the intensification of precipitation due to climate change, the El Niño phenomenon, and high intensity seismic movements because it is a seismic zone.

The study highlights the low level of citizen participation, and suggests involving the population with the local government and promoting policies for greater community participation in civic events, sports, cultural activities, and emergency training to strengthen them at the community level and reduce their vulnerability to loss of life and economic losses.

It is recommended that the municipality implement policies to improve infrastructure in the area, implement an ecological slope stabilization project, and prepare technical contingency plans and emergency mitigation plans.

Supplementary Materials: The following are available online at https://drive.google.com/drive/folders/13Kei6j_RiDxLWsLtN22hAvaU6c236p8?usp=sharing, Survey Geo – SAT, Survey validation 01, Survey validation 02, and Survey validation 03.
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References


5. Lizarralde, G; Bornstein, L; Robertson, M; Gould, K; Herazo, B; Anne-Marie Petter, A.M; Páez, H; Diaz, J.H; Olivera, A; González, G; López, O; López, A; Ascui, H; Burdiles, R; Bouchereau, K. Does climate change cause disasters? How citizens, academics, and leaders explain climate-related risk and disasters in Latin America and the Caribbean. 2021. International Journal of Disaster Risk Reduction. Volume 58, 102173.


8. Zhong, S; Wang, M; Zhu, Yi; Chen Z; Huang X. Urban expansion and the urban–rural income gap:


https://hdl.handle.net/20.500.12542/874
A data-driven design framework for greater compatibility of large-scale housing projects with user diversity and resource scarcity: a case study in Peru

The objective of this study is the development and application of a data-based optimization framework that aims to increase large-scale affordable housing projects’ design effectiveness in unpredictable scenarios with diverse users. It is based on an analysis methodology that incorporates data analytics in the design process seeking to define a concerted quality benchmark based on the identification of Key Quality Indicators (KQI’s) to be considered in order to deliver more contextually compatible and resilient housing projects. Through the identification of technical and conceptual gaps within the current housing regulations in Peru, this study aims to address their impact on design innovations and adequacy to the needs and resources of the population, focusing especially on the Housing Consolidation Processes over time. In order to provide insights that contribute to complement and update the current Design Guidelines, a PRISMA Systematic Review has been performed, obtaining 92 KQI’s of 77 Scientific Articles Reviewed, being classified in 10 Compatibility and Contemporaneity Categories. To be subsequently subjected to a Correlational Analysis with the Peruvian Housing Design Guidelines, obtaining revealing findings that were then translated into 10 General Design Premises that aim to visualize a new approach to Affordable Housing Development.

To validate the applicability of the 10 General Design Premises in a real-life scenario, these premises were applied in the Design process of a prototype presented in the VIII National Housing Competition (Peru) in a Large-Scale Housing Project located in Talara, Piura under the required regulatory standards. For the purpose of incorporating inputs from the local reality in the theoretical framework developed, a mapping process of similar pre-existing projects in the context has been made under quantitative metrics of Consolidation, Materiality and Growth Rates over the self-build and habitability processes patterns. To be then subjected to a Correlational Analysis with the 10 General Design Premises, validating its compatibility and materialized in an Affordable Housing Prototype that is a precedent of the usage of the data-based design optimization frameworks for more effective future developments.

Keywords
Affordable Housing,
Design-to-Value, Large-Scale Projects, Data Analytics, Key Quality Indicators, Mass Customization.
1. Introduction

Affordable Housing is an opportunity to operate at the limit of architectural practice, embracing the challenge of obtaining the best achievable result in scenarios of scarce resources and high rates of precariousness. Within this concept, Progressive Affordable Housing emerges as an architectural-financial strategy that seeks to make the affordability of housing units viable [1], based on a strategy of progressive investment and growth over time, that starts in a basic initial housing unit that expands in stages according to the needs of users and available resources [2]. A collaborative concept with great potential, based on the complementarity of the initial architectural design as a framework and the subsequent self-build modifications by the users [3].

Nevertheless, over the years many Progressive Affordable Housing Projects, such as the selected objects of study as ENACE I-II-III and Luis Negreiros Residential Complex, did not achieve the expected results. Putting in evidence the feasibility of this architectural strategy especially in large-scale housing projects that involve mass-produced standardized models that seem to be incompatible with the diversity of users and local characteristics, as observed on the current low consolidation and quality indexes.

Mass Production seeks to reduce the price per unit, making construction more efficient and the acquisition of basic housing units more accessible, in order to cover the quantitative housing deficit in Peru [4-6]. However, the lack of adaptability and customization attributes in the standardized models increases the local qualitative deficit, evidencing the need to not only build more but also better housing. Rigid typologies and closed construction systems, in the long term, increase the costs of expansion and adaptation, offsetting the initial financial benefits. It is therefore necessary to find new ways to anticipate and achieve greater effectiveness in the architectural design of progressive affordable housing [2], where data analysis stands out as a tool with great potential to understand trends and housing patterns of a diverse large population.

2. Problem

The main problem is based on the incompatibility of the Housing Design Guidelines and informal self-build criteria, which leads to the continued investment and development of large-scale affordable progressive housing projects under an inaccurate approach, making the efforts made to mitigate the 1.6 million Housing Deficit in Peru less effective [5,6]. In addition to resulting in long-term negative impacts on the user’s life quality and a negative balance on investment’s efficiency due to the remediation costs be assumed by the users to meet the desired design attributes that should have been considered in the initial design, which makes affordable housing even more expensive.

We disaggregated this main problem into three complementary problems that allowed us to address it from an adequate perspective. The first complementary problem approaches the complexity and relativity in defining a “Quality Standard” of Affordable Housing, in the absence of a system of metrics that would allow us to identify Key Quality Indicators agreed upon by several authors. The second complementary problem focuses on the housing regulations gaps related especially to innovation, adaptability, and the incorporation of self-build architectural criteria. Gaps that lead to interpretations that potentially increase the percentage of error and informal solutions. And the third complementary problem, which is based on the lack of data on affordable progressive housing, aiming at the need of data collection methodologies and analysis structures that facilitate the understanding of Self-Construction patterns and habitability dynamics as essential inputs for the design of large-scale housing projects towards a more scalable solution.

The focus of our study is oriented towards the analysis of the impact of the design process’ optimization in the search for an intersection between the benefits of mass production and the need for an adaptable architectural solution compatible with the diversity of contemporary users [7]. Achieved
by a systematic review and a correlational analysis between the Key Quality Indicators, the Peruvian Housing Regulations and the Self-Construction Patterns observed in pre-existing projects in Talara (Piura-Perú) site of the VIII National Competition for Affordable Housing.

3. Methodology

This study is structured on 3 phases of analysis,

a) Theoretical-Conceptual Analysis

Collection and Selection of an Unstructured Literature by using the PRISMA Systematic Review: A total of 77 Scientific Articles were reviewed in order to identify the most relevant characteristics, concepts, and criteria to be applied in Innovation Models for Affordable Housing. Which were obtained from reliable databases such as SciELO, Redalyc and various repositories of universities around the world. These were processed under the PRISMA protocol that contemplates 27 criteria and 4 phases, obtaining 24 selected studies, Figure 1, that comply with documentation validity, descriptive references to Affordable Housing, Quality and Regional/Global Scope among others.

Concepts and Criteria Classification: The data extraction process was performed through the use of affinity matrices, where the most relevant theoretical-conceptual contributions collected in the previous phase were classified into two systems of Key Quality Indicators (KQIs); Compatibility’s 5 Dimensions: I Typology, II Growth Strategies, III Constructability, IV Sustainability, V Economic Capacity and Contemporaneity’s 5 Historical-Temporal Quadrants: I (1929-1950), II (1950-1976), III (1976-1996), IV (1996-2016), V (2016-2020). Figure 2. Both KQI’s Systems were synthesized in double-entry matrices as an adaptable input tool for the following correlational analyses.

Correlation Analysis with Peruvian Housing Regulations: It was performed a correlation analysis between the classified theoretical indicators and the most relevant Housing Regulation Documents in order to identify their level of contemporaneity.
and compatibility under two variables (compatible or not compatible). A study that covers Peru’s National Building Regulations (RNE G.010 Basic Considerations, G.020 General Principles, G.040 Definitions, A.010 General Design Conditions, A.020 Housing, A.120 Accessibility, E.010-E.090 Structures and IS.010 Sanitary Installations), the National Housing and Urban Planning Policy, Operating Regulations of the MiVivienda Fund, Bases of the VIII National Housing Competition and the Sustainable Urban Development Law. Figure 2.

Figure 2. Scheme of separation of studies in indicators of Compatibility and Contemporaneity.

b) Site Diagnostic Analysis

Unstructured Data Collection through Mapping of Pre-Existing Projects in the Context: The VIII National Housing Competition was located in Talara, Piura (Peru). In order to incorporate the local habitability and self-construction patterns as an input in the design process, a process of mapping and descriptive survey of 2017 Units was performed, covering the Projects ENACE I-II-II and “Luis Negreiros” Residential Complex. This process had to be done virtually through GIS Tools such as Google Maps and Google Earth, due to health restrictions resulting from the COVID-19 Pandemic that was taking place while the study was being developed (2020-2021), with the aim of safeguarding the integrity of the research team as well as the local communities in a unprecedented global scenario.

Classification Parameters and Pattern Analysis: The selected parameters for classifying the information obtained from the mapping process were I Growth Trend (Horizontal/Vertical), II Type of Materials used in the Self-Construction Process (Artisanal/Industrial) and III Level of Consolidation (Nonexistent/Partial/Complete). Figure 3. It was performed under a descriptive and interpretative analysis of the patterns observed through surveys and photographic evidence. Translating them into general quantified conclusions, in order to validate the scope of compatibility of the proposed design solution, considering the high impact of design decisions especially in large scale projects.
3. Compatibility and Integration Analysis (1+2)

Correlation Analysis between Theoretical-Conceptual Framework and Site Analysis Patterns: A correlational analysis was performed with the purpose of defining an optimal articulation between the theoretical approach and the real conditions of the context. This was achieved by contrasting them and measuring their potential complementarity based on the level of impact within the system. Make it able to identify the ultimate Key Quality Indicators to be implemented in the design process of the Housing Prototype. Figure 4. This analysis aims to encourage an integrated and strategic approach of innovative concepts, regulations guidelines, and real-life lessons for a more effective design.

4. Results and Findings

The mission of our study was to contribute to building bridges between the theoretical-conceptual approach with the real needs, expectations, and resources of affordable housing users, in order to reach a more effective architectural design in the long-term [8,9]. This study sets a precedent with a data-based optimization framework for large-scale affordable housing projects, which is supported by the results of the processes performed in the analysis phase that are organized in the 3 following parts:
a) Theoretical-Conceptual Results

The study provides a concerted Quality Standard for Affordable Housing with objective 93 Key Quality Indicators supported by several authors and studies through the PRISMA Systematic Review. Setting a benchmark that brings objectivity in the decision-making debate during the design process, as shown in this case where it has been defined 10 General Design Guidelines, Figure 5, based on the KQI’s for Affordable Housing in Perú that are the following ones:

1) Multifunctionality instead of reduction towards greater efficiency of spatial use.
2) Standardization of building components rather than the users and their lifestyles.
3) The architectural project has to regulate and guide the self-build extensions.
4) Progressiveness has to be contemplated in all the specialities involved.
5) Prevalence of fundamental habitability attributes during all growth phases (light and ventilation).
6) Collaborative-frameworks of Housing design between users and professionals.
7) Multiscale modulation that allows growth parameters compatible with the urban model.
8) Flexibility as a key to the prevalence of functionality without significant changes.
9) Electrical and Sanitary Installations designed for future expansions.
10) Inclusion of a productive space to promote self-financing dynamics for housing consolidation.

Figure 5. Graphics of the design guidelines for affordable housing and explanatory graphic of the environmental measures applied.

Secondly, it has been created a compatibility and contemporaneity measurement tool that could help to identify the gaps in the Housing Guidelines and quantify the qualitative indicators in order to improve the Housing Regulations and anticipate the potential problems related to them through a strategic architectural design. The case of study highlights among other results, that the Peruvian Housing...
Regulations has a conceptual architectural lag of 70 to 90 years [4-5,9-11], evidencing the necessity to update and change the paradigm of repetitive mass-produced model’s characteristic of the Historical-Temporal Quadrant I (1929-1950). Which are especially incompatible with a hyper-diverse society that needs adaptability and customization features [7,12] within the standardized models in order to reach the optimal self-build expansion and consolidation over time.

In addition to that, the study shows a lack of long-term planning on Housing Regulations based on the non-contemplation of the complete process of transformation and consolidation of Housing’s lifecycle (Appropriation, Adaptation, Expansion, Consolidation, Subdivision and Sale/Rent) where only 3 of the 6 phases of development are considered, leaving regulatory gaps that allow misinterpretations which consequently encourages informality and increases the percentage of error. The Regulations show greater compatibility with the Key Quality Indicators between the first 3 phases with 56.88%. However, from the expansion phase to the later phases the indicators decrease with only 8% of compatibility with the ideal indicators.

b) Site Diagnostic Results

Because of a lack of data on affordable progressive housing, this study represents a precedent of Mapping and Data Collection Methodology, setting an analysis methodology to perform a pattern identification and analysis of self-build and habitability processes. Which contributes to measure and validate a theoretical solution with real-life numbers quantified through the following parameters: Growth Trend (Horizontal/Vertical), Type Materials (Artisanal/Industrial) and Levels of Consolidation (Nonexistent/Partial/Complete). The results of the analysis performed in 2017 show that there’s a greater difficulty in Vertical Growth (4%) due to its structural and constructive complexity. On the other hand, there’s a partially balanced proportion between the use of Industrial (43%) and Artisanal (57%) materials can be observed, evidencing the need for hybrid construction strategies based on the local labor skills. Finally, given the low rate of fully/partially consolidated units (16%) it is necessary to rethink strategies that facilitate self-build extensions while guaranteeing their constructive, functional, and structural integrity.

c) Compatibility and Integration Results

One of the most important values observed in the results of this study is the identification of complementarity potential between the different elements that converge in the Development of an Affordable Housing Project. This study has shown that the proposed data analysis structure could contribute to visualizing and prioritizing high-impact interventions under a coordinated design strategy. Matching theoretical and conceptual KQI’s with specific context conditions, anticipating problematics that emerge from the Housing Regulation gaps through proactive design strategies, incentivizing the creation of a database of self-build pattern in informal contexts in order to measure and visualize more accurately the requirements and expectations of the future users [1-3,12-14]. Figure 6. This study aims to incentivize the need for a balanced vision that integrated innovation concepts [1-2, 8-9], regulatory guidelines and real-life lessons for a more effective design looking to achieve greater effectiveness in large-scale projects with a diverse user’s structure. In this study the ultimate KQI’s has been translated on 4 Key Data-Driven Innovation Design Strategies applied in the Prototype Development, which are the
following:

1) Horizontal Expansion on Upper Levels: Based on the data pointing the predominant trend towards horizontal growth (40%), the aim is to facilitate the vertical consolidation of the unit by allowing horizontal growth under the particularity that it will be applied to the upper levels by creating structural frames designed to accommodate self-build horizontal expansions.

2) Reducing the Complexity of Self-Build Expansions: Based on the data referring to the non-existence of expansions in 56% of the units analyzed, the premise of facilitating the self-construction process arise by reducing the complexity of the self-build expansions, where the initial unit provided by professionals assumes most of the structural responsibility for the unit, allocating less complex tasks to be performed by the users, such as the completion of the building envelope to create internal spaces.

3) Hybrid Structure: Based on the data indicating the use of Industrial (43%) and Artisanal (57%) materials in the pre-existing units in the context, the project encourages the complementarity of industrialized components as prefabricated modular steel for the core structure, with local techniques and materials as wood or plywood for the self-build expansions.

4) Progressive Investment for Progressive Growth: Based on the data referring to the rates of non-consolidation (84%) and total/partial consolidation (16%), we intend to facilitate the overcoming of the financial barrier, synchronizing the costs of each different phase and their constructive complexity, with the financial evolution of the user’s purchasing capacity over the years.

Figure 6. Initial housing prototype and long-term expansion.
5. Discussion and Conclusion

The gap between theory and reality is not a new debate; throughout history it has been erroneously conceived that one is exclusive of the other. However, the solution lies in the concordance and complementarity between the two, in order to be able to propose quality and high impact solutions. This research is an effort oriented to encourage the integration between conceptual theoretical research and its applicability in real housing development scenarios [15]. It is due to this that the scope of the research reaches the application stage in a prototype, figure 6, intended to be replicated in over 200 units in the VIII National Competition of Affordable Housing, meaning a methodological and architectural precedent of the viability of Innovation Strategies in Progressive Affordable Housing.

It is important to address the housing deficit in its two dimensions, quantitative and qualitative. Peru has a Housing Deficit of 1.6 million units, of which 1.47 million are of a qualitative nature [5,15-16], revealing trends of habitat precariousness that must be urgently addressed. Through this study, we intend to provide objectivity to the debate on the definition of Affordable Housing Quality Standards, considering that agreeing on the qualitative criteria to be achieved is an essential first step to move in the right direction to make it a reality, especially in a scenario where the Peruvian Housing Regulations [5] prioritize the quantitative attributes.

However, we must continue to encourage a better understanding of the needs of the population in order for projects to effectively address them. Therefore, this study aims to visualize the importance of creating analysis structures and databases of Affordable Housing Projects to help gather valuable information and accurately visualize all the patterns and trends behind the self-construction and habitability processes [17,18], allowing architects to make better design decisions.

This study intends to encourage us to review our internal and external processes, to evaluate and understand the impact of the Housing Regulations that we are applying into our design projects and also to incentivize the analysis of the Built Environment that surrounds us. It is an important precedent towards the exploration and innovation of Affordable Housing with the purpose of increasing the % of compatibility between the architectural project and a diverse large-scale population. In these conditions, the effectiveness of the design is directly related to the ability of a standard solution to adapt to different users [7,12,14,19-20], with different lifestyles, needs, resources and expectations without losing the benefits of economies of scale and massive production [3,15,19]. We intend to contribute to the search for collaborative strategies that help achieve a balance between resilience, financial accessibility, and architectural quality for future Affordable Housing Projects.

References


Indoor environmental quality and energy performance: Reviewing the case of council homes in London

In the UK, exposure to air pollution constitutes the most significant environmental risk to public health, particularly for low-income groups residing in council homes. These occupants often live in smaller flats at higher densities, which are typically located in areas with higher levels of air pollution. Consequently, their health and well-being are negatively impacted. Moreover, in the quest for improving indoor thermal comfort and energy efficiency, the levels of airtightness increased, and the ventilation rates decreased, which have further worsened indoor air quality. Therefore, this paper critically reviews the trade-offs between airtightness, indoor air quality (IAQ), thermal comfort, and their impacts on building occupants’ health and well-being. The paper focuses on the case of London, where action plans and retrofitting strategies of council homes are reviewed. The review aims to explore strategies to optimize and balance between energy efficiency, indoor thermal comfort, and indoor air quality. Based on the review, the paper proposes the adoption of the social approach, in addition to the physical measures, through the consideration of the occupants’ behaviour and altering their behaviours to optimize the use of energy and improve their indoor living conditions. The paper also recommends different mitigation strategies and design guidelines to promote healthier and more energy efficient buildings.

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1. Introduction

In 2021, the residential sector in the UK accounted for approximately 16 per cent of greenhouse gas emissions, with roughly 97% of the gases attributed to carbon dioxide [1]. In addition, the indoor environment in these households can have a significant impact on people's health due to the extended duration spent in these microenvironments. In developed countries like the United Kingdom, people spend around 90% of their time indoors [2], with around two-thirds of their overall time spent within residential buildings [3]. According to the World Health Organization [4], in 2020, household air pollution was responsible for approximately 3.2 million deaths. Furthermore, indoor air pollution has been identified as the third leading cause of disability-adjusted life years worldwide [5]. Focusing on the United Kingdom, air pollution exposure represents the most significant environmental health threat, resulting in 28,000–36,000 premature deaths annually. In London, poor air quality is also linked to approximately 9,400 premature deaths annually due to elevated levels of PM2.5 and NO2, resulting in a financial burden of £1.4 to £3.7 billion on the healthcare system [2, 6, 7].

Various adverse health outcomes are also associated with these elevated exposure levels to air pollution, including respiratory and cardiovascular complications, birth defects, childhood asthma cases, and sudden infant deaths. Additionally, air pollution has been estimated to have a detrimental impact on cognitive functions, leading to cognitive impairment and an increased risk of dementia [2]. The impact of air pollution in homes on human health and well-being occurs through various environmental pathways, including: (1) household air pollution originating from activities such as cooking, heating, and lighting, especially when reliant on rudimentary biomass, heating stoves, and coal cooking; (2) indoor air quality affected by dust or gases emitted by hazardous building materials and radon, as well as exposure to extreme temperatures (either hot or cold); (3) exposure to disease-carrying vectors, including pests and insects; (4) exposure to dampness and mould; and (5) utilization of unsafe construction materials and inadequate construction practices [5, 8].

Given these severe impacts, concerns over indoor environmental quality (IEQ) and energy efficiency in residential buildings have gained greater importance and the reduction of emissions from residential buildings became inevitable. Energy efficiency in buildings aims to minimize energy consumption while ensuring occupants can perform their daily activities, all while maintaining an optimal indoor environmental quality. Indoor environmental quality, simultaneously, refers to the physical and psychological aspects of indoor environments that influence the well-being, comfort, and contentment of occupants. Therefore, it is imperative to implement energy-efficient strategies and other measures that aim at mitigating indoor air pollution and emissions in the residential sector. This can also contribute to the mitigation of other problems like fuel poverty, household energy insecurity, and the negative health impacts associated with winter and cold conditions, including mortality and morbidity [9].

The significance of both indoor environmental quality and energy efficiency in residential buildings cannot be overstated. They are crucial for safeguarding the health, well-being, and productivity of occupants, while simultaneously reducing carbon emissions and energy expenses associated with buildings. These problems are particularly challenging for low-income groups residing in council homes. These occupants inhabit smaller flats with higher population densities, often located in areas characterized by elevated levels of air pollution. Consequently, their physical health and overall well-being are negatively impacted. In addition, efforts to enhance indoor thermal comfort and energy efficiency have resulted in increased levels of airtightness and decreased ventilation rates, which further exacerbated indoor air quality issues.

Thus, this paper aims to comprehensively understand the various synergies and trade-offs between airtightness, indoor air quality (IAQ), and thermal comfort, and their respective impacts on the health and well-being of building occupants. An overview of the circumstances in London is presented, examining the diverse factors that contribute to low-income households experiencing higher levels of indoor air pollution compared to the general population. This analysis is based on studies and models specific to London. Based on the review, strategies for balancing energy efficiency, indoor thermal
comfort, and indoor air quality are presented. The paper recommends the adoption of the social approach in addition to the physical measures in building retrofits and energy simulations. This encompasses the consideration of occupants’ behaviours and modifying their habits to optimize the use of energy and enhance their indoor living conditions.

2. Indoor environmental quality, and energy efficiency: Synergies & trade-offs

In the pursuit of enhancing indoor thermal comfort and energy efficiency, there has been a significant rise in airtightness levels and a corresponding decrease in the ventilation rates. However, these measures have adversely aggravated the issue of indoor air quality. This section aims to examine the effects of increased thermal insulation and air tightness on the overall indoor environmental quality and energy performance of residential buildings.

Thermal conditions and air quality were considered by the occupants to be two of the most important indoor environmental parameters determining comfort [10]. In today’s buildings, thermal comfort is directly related to indoor air quality (IAQ), which in turn depends on envelope airtightness in buildings with no active ventilation systems [11]. Envelope airtightness and thermal insulation are used to help in: 1) reducing the amount of energy consumed for heating/cooling by limiting the number of air changes, 2) ensuring conditions for indoor thermal comfort, and 3) controlling moisture [12, 13]. The term “insulate-air tightening” was used by Yoshino [12] to refer to thermal insulation and air tightening in one word.

However, reducing air permeability in buildings by implementing highly airtight building envelopes can have significant implications for indoor air quality. This reduction in air infiltration leads to an increase in the concentration of water vapor and carbon dioxide, which are byproducts of human metabolism and considered major contributors to indoor environmental issues. In residential dwellings, occupants’ behaviour can exacerbate these problems. For instance, when residents use cooking appliances with open flames to warm the interior, the indoor air experiences elevated moisture content and concentrations of harmful gases, including carbon monoxide and dioxide [13].

Furthermore, it is important to note that thermal insulation alone does not always result in a better indoor environment [12]. A recent study conducted in the UK revealed that improved building performance, while increasing thermal insulation and airtightness, can potentially lead to over insulated building envelopes that are more prone to overheating during warmer seasons, especially when subjected to direct solar radiation. These findings underscore the significance of considering occupancy scenarios for different households to accurately predict overheating risks and prevent complications in retrofit interventions, which will be discussed in section 5 [14].

In addition, insufficient ventilation in indoor spaces is a significant factor in the prevalence of sick house syndrome (SBS). SBS refers to the negative impact on the comfort and well-being of individuals in a building. Apart from its detrimental effects on occupants, a sick building is often associated with low energy efficiency, which can be attributed to various design, implementation, and operational flaws in the building and its systems. These issues highlight the importance of addressing ventilation deficiencies and improving overall building performance to ensure healthier and more energy-efficient living environments [13].

The sick house phenomenon can be attributed to several factors, including reduced natural ventilation resulting from a tightly sealed building envelope. Additionally, the use of certain building materials, furniture, and everyday items containing chemicals, as well as the presence of substances like mothballs and air fresheners, and other pollutants contribute to the problem. These factors collectively contribute to the development of an unhealthy indoor environment with potential negative impacts on occupants’ well-being [12].

As a result, ventilation is imperatively important in the design of residential buildings. Firstly, ventilation aims to prevent the build-up of air pollutants such as chemical substances, carbon dioxide,
nitrogen oxides, and unpleasant odours. Secondly, it serves to remove excess moisture from enclosed spaces. Lastly, ventilation plays a crucial role in supplying an adequate amount of oxygen to combustion devices. To achieve effective ventilation, it is essential to ensure the airtight performance of the building. This can be accomplished by introducing outdoor air through properly designed air supply inlets, allowing it to circulate through all areas of the indoor spaces, and efficiently expelling it through exhaust systems. Particularly in spaces where chemical emissions may occur, the introduction of fresh outdoor air to all areas becomes paramount [12].

Finding the optimal ventilation rate in residential dwellings is a trade-off between minimizing heat loss for meeting greenhouse gas emission targets and minimizing adverse health effects caused by exposure to cold temperatures and pollutants from both indoor and outdoor sources. In a preliminary application of the methods to a typical flat and detached house in the UK [15], it was observed that the optimal ventilation rate can vary depending on the building form. The analysis indicates that the flat may require a higher ventilation rate compared to the detached house. By employing a generalized multi-objective optimisation approach with equal weightings given to health impacts and energy savings, an optimal annual air changes per hour (ACHyr) of 0.4/h for the house and 0.7/h for the flat was determined. These values include purge ventilation during periods of indoor PM2.5 and moisture generation, corresponding to average ventilation rates of 0.3 l/s/m² for the house and 0.4 l/s/m² for the flat [15].

Effective control of moisture, carbon dioxide (CO₂), and airborne pollutants necessitates a balance between introducing fresh air from the outside and extracting stale air from the indoors. Retrofitting measures are often implemented to enhance energy efficiency by improving airtightness in homes. However, as homes become more airtight, it becomes imperative to install controllable ventilation systems to ensure consistently high air quality. A recent study conducted by the London Councils [16] identified heating systems, and mechanical ventilation with heat recovery (MVHR), to have the greatest impact on occupants’ health (based on subjective assessment of the impact of retrofit measures on the second-order effects). Consequently, it is of utmost importance to prioritize the development of ventilation systems in building retrofitting plans to enhance both health and indoor air quality.

3. Indoor air quality & socioeconomic disparities: Reviewing the case in the UK

Numerous studies have focused on investigating the associations between environmental inequality and health [2, 17-20]. These studies have recognised the significant links between pollution, deprivation, and health. Within the field of environmental health, this phenomenon is commonly referred to as the ‘triple jeopardy’ effect. The ‘triple jeopardy’ phenomenon states that communities with lower socioeconomic status (SES) residing in deprived areas face a threefold challenge. They experience elevated exposure to air pollutants and other environmental hazards, such as air pollution. Besides, they display an increased susceptibility to poor health, primarily due to elevated psychosocial stressors, including discrimination and chronic stress, limited opportunities to engage in health promoting behaviours, and overall poorer health status. As a result, these circumstances lead to the emergence of health disparities that are primarily driven by environmental factors [2, 21].

In the UK, extensive research has long acknowledged the links between low socioeconomic status (SES) and poor IAQ. The two UK studies conducted by Pearce, Richardson [22] and Fecht, Fischer [23] have found that individuals from low SES groups tend to experience poorer air quality compared to their counterparts. Furthermore, in England, the gap in health inequalities has widened between 2001 and 2016 (Bennett et al. 2018), where occupants residing in the most deprived areas of the country face a threefold higher risk of death from preventable health conditions compared to those residing in the least deprived areas, according to data from the Office for National Statistics in 2019 [2]. The exposure to air pollution has been explicitly highlighted in the 2019 Public Health England’s (PHE) remit letter as one of the leading factors contributing to preventable health issues (Ferguson, Taylor et al., 2021). Thus,
the reduction of environmental inequalities shall be prioritized. Ferguson, Taylor [2] in their paper examine the factors that contribute to higher levels of indoor air pollution in low-income households compared to the general population, using models and datasets for London. The study has outlined five important factors driving indoor air pollution exposure disparities. These factors include:

1. Living in deprived areas with often higher levels of outdoor air pollution.
2. Inadequate housing conditions:
   a. Low socioeconomic status groups tend to live in smaller dwellings with limited external facades, hindering the removal of both outdoor-sourced and indoor-generated pollutants.
   b. Indoor sources of pollutants, such as gas cookers, heating systems, smoking, and cooking styles, further contribute to indoor pollution.
   c. Increased airtightness in low-income housing reduces the removal of indoor-generated pollutants.
   d. The physical layout of buildings also plays a role, as smaller volumes lead to higher concentrations of pollutants without sufficient ventilation. Low-income households face challenges in maintaining proper ventilation systems. Besides, living in flats with shared walls and floors increases the risk of pollutants from neighboring dwellings entering the home, especially in high-density housing.
3. Occupant behaviour also plays a crucial role in indoor air pollution levels. For instance, low-income households are characterised by longer cooking durations resulting in substantially higher indoor air pollution levels.
4. Additionally, residents of low-income households spend more time at home, often due to unemployment or security concerns in their neighborhoods. Overcrowding and high occupant density further contribute to poor indoor air quality.
5. Underlying health issues; respiratory and cardiovascular diseases have been identified as major contributors to the increasing health disparities between the most and least deprived regions in the UK over the past two decades. These diseases are more prevalent in areas of lower socioeconomic status, intensifying the adverse effects of air pollution exposure on health.

In conclusion, low-income groups face a triple jeopardy situation where they experience higher levels of indoor air pollution due to factors such as the physical properties of the household, their socioeconomic status, their behaviours, and their preexisting health conditions that further exacerbate the health impacts of exposure compared to those without such conditions. As their health deteriorates, individuals may be compelled to spend more time indoors, leading to an increased exposure to air pollution within the domestic environment.

4. Energy-efficient retrofitting of council housing: Reviewing the case in London

This section reviews the national and local initiatives for building retrofitting in London and the
UK. The current retrofitting strategies and efforts within council homes are outlined. In addition, the barriers and enablers to energy efficiency retrofitting of social housing in London are demonstrated. National and local scale initiatives for energy efficiency in the UK are outlined. In addition, the barriers and enablers to energy efficiency retrofitting of social housing in London are demonstrated.

In England and the UK, national level initiatives have been proposed to address energy efficiency in buildings. These initiatives involve:

a) Policy measures for the private rented sector (minimum Energy Performance Certificate (EPC) rating of C by 2030) and for mortgage lenders as well,

b) The Construction Leadership Council has drafted a National Retrofit Strategy that emphasises local leadership and collaboration through partnerships for effective implementation,

c) Funding initiatives have also been introduced, such as the Green Homes Grant Local Authority Delivery scheme and energy efficiency projects supported by the Department for Business, Energy and Industrial Strategy (BEIS).

Furthermore, local initiatives and guidance plans are also in place. For instance, Nottingham Deep Retrofit Energy Model, Greater Manchester Combined Authority: People Powered Retrofit with URBED & Carbon Coop, and UKGBC Accelerator Cities Programme, including the Retrofit Playbook. These initiatives collectively aim to drive sustainable retrofit programs, improve energy performance, and promote the adoption of energy-efficient practices in the built environment [16].

Buildings in London have a significant impact on the city’s carbon emissions, contributing to almost 80 percent of the total. Additionally, these buildings emit pollutants like nitrogen dioxide and particulate matter, which have direct health implications for the residents of London. Therefore, enhancing thermal comfort and indoor air quality can significantly benefit health, particularly for vulnerable populations. According to the International Energy Agency (IEA) and the Organisation for Economic Co-operation and Development (OECD), health improvements may contribute up to 75% of the overall value derived from enhancing the energy efficiency of buildings. Additionally, HACT’s Social Return on Investment calculator indicates that a 3-point improvement in Energy Performance Certificate (EPC) ratings in London can lead to enhanced well-being for individuals, amounting to an estimated £651 per year. Therefore, it is crucial to assess home retrofitting not only in terms of energy conservation but also in terms of positive health effects and other associated benefits, often referred to as co-benefits [16]. Accordingly, tackling air pollution and energy efficiency have been prioritised in London’s plans and policies [24].

Current initiatives and retrofitting progress in London Boroughs

London boroughs have a significant level of control over their own housing stock. This level of control provides an opportunity to implement large-scale retrofitting initiatives over the next decade and beyond. Nearly all London boroughs are actively engaged in the development of effective retrofit initiatives, aiming to establish and promote best practices, as shown in Table 1. These initiatives encompass a wide range of projects, including demonstration projects for both individual houses and blocks of flats [16].
Additionally, there is a specific focus on activities related to heat decarbonisation, renewable energy generation, demand flexibility, and strategic endeavours related to delivery, cost assessment, funding, stock assessment, and modelling. These comprehensive efforts reflect the commitment of London boroughs to advance sustainable retrofitting practices and drive positive change in the built environment. Moreover, the Retrofit Accelerator - Homes programme was developed to assist London boroughs and housing associations in implementing large-scale energy efficiency projects. The programme offers technical and commercial solutions to support the development of these initiatives. Furthermore, homeowners and professionals in London have various resources to support energy efficiency initiatives. These resources include reports published by the Greater London Authority (GLA) on topics such as heat pump retrofit in London (2020) and Building Renovation Passports (2021). By incorporating energy-efficient retrofit measures into the ongoing maintenance programs and establishing clear and measurable targets, London local authorities can effectively drive the progress towards achieving low-energy standards in their housing stock [16]. The London Councils [16] have also developed a set of recommended actions to retrofit the councils’ own stock, as demonstrated in Table 2.

**Table 2.** Recommended action to retrofit the councils’ own stock by the London Councils [16]

<table>
<thead>
<tr>
<th>Demonstration Project</th>
<th>Delivery, skills, supply chain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Houses:</strong> Brent, Enfield, Lewisham, Newham, Richmond, Sutton, Wandsworth, Waltham Forest</td>
<td><strong>Skills:</strong> Camden’s stakeholder engagement event</td>
</tr>
<tr>
<td><strong>Block of flats:</strong> City of London, Enfield, Greenwich, Hackney, Haringey, Kensington &amp; Chelsea, Redbridge, Richmond &amp; Wandsworth, Sutton</td>
<td><strong>Energiesprong:</strong> Enfield, Haringey, Sutton</td>
</tr>
<tr>
<td><strong>Window manufacturing:</strong> Newham</td>
<td><strong>Parity Projects’ Ecofurb</strong></td>
</tr>
</tbody>
</table>

1. Improve the building fabric of London’s inefficient homes
2. Develop a plan for retrofitting ventilation systems to improve health and air quality
3. Electrify heat
4. Deliver smart meters and demand flexibility (controls, storage) in retrofitted homes
5. Increase solar energy generation on London homes
6. Map out each building’s journey towards lower energy costs and Net Zero
7. Review current maintenance programmes and identify retrofit opportunities
8. Facilitate procurement of materials and services at a larger scale
9. Enable planning to facilitate low carbon retrofit, including in Conservation Areas
10. Develop retrofit skills actively across London
11. Set up a clear and consistent system to report and monitor progress (and success)
12. Establish the cost of retrofit, business case and funding gap for the different tenures
13. Maximise capital finance for council-owned stock (and eligible homes)
14. Create a ‘Finance for retrofit’ taskforce with finance experts
15. Social housing; engage with tenants, leaseholders and other registered providers
16. Continually develop and implement the Action Plan together
Barriers and enablers to energy efficiency retrofitting of social housing in London

Though huge efforts were demonstrated in the field of energy retrofitting to residential buildings in London, it was still recognised that there were not enough retrofits. It is critically important to understand the key barriers to residential retrofitting in London. One of the main attributed reasons was the lack of regulatory framework [16]. The current regulatory framework lacks adequate support for improving the energy efficiency of existing homes, transitioning away from gas boilers, and implementing solar PV systems for electricity generation. It falls short in promoting comprehensive whole house retrofitting and decarbonisation of heating systems. Besides, supportive initiatives remain very limited in scale and primarily focus on individual measures rather than adopting a holistic approach to retrofitting. As a result, they have not yet reached the necessary scale to make a significant impact [16].

Other challenges are also faced throughout the different retrofitting stages. In that sense, two significant studies were concerned with overviewing the key challenges. First, the report conducted by the London Councils [16] categorized the challenges into four main groups, as follows:

- **Technical:**
  
The complexity of retrofitting requires tailored solutions for each home and household, striking a balance between simplification and specificity. However, the current approach fails to achieve this balance, leading to confusion and inadequate recommendations for homeowners and landlords.

- **Finance:**
  
The majority of landlords and homeowners face financial constraints that prevent them from undertaking whole-house low carbon retrofit in a single phase. This challenge extends to occupants of social housing as well. Local authorities have the potential to facilitate finance for all properties within their jurisdiction, including non-council owned social housing. However, limited resources pose significant obstacles, hindering the funding of retrofit projects even for their own housing stock. London’s local authorities have made a collective commitment to retrofit the city’s building stock to achieve an average Energy Performance Certificate (EPC) rating of B by 2030. Furthermore, many authorities have declared a climate emergency and set a target of achieving net-zero emissions by the same year. However, the challenges of financing and limited resources pose significant obstacles for local authorities, who are under immense pressure. Mobilizing substantial amounts of public and private finance is crucial for successful retrofitting efforts, and achieving this requires effective coordination at both local and regional levels.

- **Delivery and supply:**
  
Meeting various obligations and priorities, such as affordable housing provision, building safety improvements, and post-Covid-19 recovery, creates additional complexities in the delivery of retrofit projects. Once homeowners and landlords have determined their retrofit plans, the challenge lies in accessing a reliable and high-quality supply chain capable of effectively implementing the proposed measures.
Second, Peel, Ahmed [25] were concerned with investigating the barriers and enablers to energy efficiency retrofitting in social housing in London, UK. Based on literature review, interviews and surveys with key stakeholders within the housing stock, they grouped the barriers and enablers into seven categories. These are: financial matters, Technical, IT, Government policy and regulation, social factors (including awareness of the energy efficiency agenda), quality of workmanship and disruption to residents. Similar to the findings of London Councils [16], financial issues, technical complexities, and government policy and regulation were identified as the primary significant barriers and enablers to energy efficient retrofitting in social housing (EERSH).

5. Discussion

The key findings derived from this study highlight the need for collaborative efforts between government, its agencies, and professional bodies to address knowledge gaps and implement technological interventions. Incentivisation is identified as an important tool to improve poor indoor environments. In addition, based on the results from this study, various potential interventions, and strategies for improving indoor environments and retrofitting residential buildings are also proposed. These interventions can be categorized into three main areas: improving outdoor environments, enhancing housing quality and urban form, and changing the behaviour of occupants.

First, improving outdoor environments involves reducing emissions from outdoor sources, increasing green infrastructure, and improving access to high-quality, safe, and low-traffic outdoor spaces. These interventions have multiple benefits, including reducing outdoor air pollution levels and its subsequent infiltration indoors, promoting physical activity and reducing underlying health issues, and potentially increasing the use of natural ventilation to remove indoor-generated pollutants. However, it is important to note that spending more time outdoors may not lead to an absolute reduction in air pollution exposure unless outdoor concentrations are significantly reduced. Moreover, investments in infrastructure are needed to reduce outdoor air pollution and traffic, improve local green spaces, safety, and amenities. This can encourage residents to spend more time outdoors and subsequently reduce indoor pollution levels. Inadequate access to green infrastructure has been identified as a driver of health inequalities, and investing in infrastructure that promotes walking can increase physical activity across different socioeconomic groups. These principles are also aligned with initiatives such as the NHS’s Healthy New Towns Programme.

Second, improving housing quality and urban form involves several measures such as enhancing airtightness and insulation, implementing effective ventilation systems for local moisture/fume extraction and recirculation, utilizing filtration methods, and installing alarming systems. Additionally, the study emphasizes the importance of analyzing and ensuring the functionality of natural ventilation systems when increasing the air tightness of building envelopes. It is also suggested that energy efficient retrofitting is a long-term solution for reducing heating energy use and improving the overall performance of buildings. These measures aim to improve indoor air quality and overall living conditions.

Third, this study highlights the importance of occupant behaviour in building performance and
energy consumption. Variations in energy consumption behaviour among households with similar characteristics pose challenges in predicting the energy-saving potential of retrofit interventions. This variability adds complexity to the task of improving energy efficiency in residential homes. Changing the behaviour of occupants is another important aspect of improving indoor environments. This includes addressing the use of chemical-emitting consumer products, combustion appliances, and optimizing the use of windows, trickle vents, and extractor fans. Raising awareness and providing education about healthy indoor environments can also contribute to behaviour change among occupants.

In the context of the social housing sector, several recommendations are proposed, including the introduction of legally binding national energy efficiency targets, stability in government policies and funding, increased grant funding for energy efficiency works, and research into innovative solutions for hard-to-treat properties. It is also suggested that engaging with tenants, leaseholders, and other registered providers, as well as developing action plans, communication tools, and coordination among stakeholders, can facilitate more efficient and effective retrofitting efforts.

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References


10. Frontczak, M.J., R. Andersen, and P. Wargocki, Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing, Building and Environment, 2012. 50: p. 56-64.


24. Greater London Authority, Mayor announces plans for new buildings to improve London air

Assessing the effect of retrofit strategies on thermal comfort and energy performance in social housing

Recently, 30 percent of the final energy consumption in the UK is attributed to residential buildings. Besides, social housing accounts for around 5 million residential properties in the UK, playing a major role in implementing energy efficiency retrofit policies in the country. This sector is home to some of the most vulnerable groups in society who are more at risk of thermal discomfort, fuel poverty, and poor environmental conditions. Hence it is crucial to consider a comprehensive approach not only to address energy efficiency but also to understand the effects of retrofit on summer/winter thermal comfort conditions. The aim of this study is to assess the effects of retrofit strategies on energy performance and thermal comfort conditions in a case study flat in the social housing sector in the UK. A building survey was conducted followed by dynamic thermal modeling in IES (VE) to evaluate the effects of upgrading the building fabric to the Part L of the UK building Regulations as well as to the passive house standards. Moreover, CIBSE TM59 and PMV guidelines have been applied to the model to assess its thermal comfort and energy consumption. The results revealed that although a high level of insulation and airtightness can reduce annual energy consumption by up to 60 percent, they could simultaneously increase the risk of overheating.

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Keywords
Thermal Comfort; buildings’ energy modeling; CIBSE TM59 guideline, passive house standard, Part L standard
1. Introduction

In the past decade, population growth, technological developments, and higher living standards have led to a substantial increase in energy consumption worldwide. Meanwhile, in the UK, implementing energy efficiency policies and regulations has played a crucial role in curbing energy demand growth in the country. In fact, the UK’s energy consumption has declined from 150 million tonnes of oil equivalent in 2010 to 120 million tonnes in 2021 [1]. Since Buildings account for almost 30 percent of energy demand in the country, implementing energy efficiency policies in this sector enables the country to sustain this trend in the coming years.

With the current annual replacement rate of 180,000, of around 28 million housing stock in the UK; retrofitting seems to be the only viable approach to improve the energy performance of buildings [2]. Retrofitting in buildings refers to the upgrading of the fabric, systems, or controls of a property without fundamentally altering its original design or structure. Retrofitting measures may include improving insulation, upgrading HVAC (heating, ventilation, and air conditioning) systems, replacing windows with more energy-efficient ones, utilizing renewable energy resources, etc. Hence, retrofitting is a common practice to transform older or less efficient buildings into more energy-efficient ones [3].

![Figure 1. Breakdown of energy consumption in existing homes](image)

The initial stage in implementing effective retrofit strategies for improving a building’s energy performance is analyzing the energy flow of the case study to provide insights into the contribution of each section to the building’s overall energy consumption. According to statistics in existing homes, as shown in Figure 1, space heating is the dominant driver of energy consumption (making up 63% of annual energy consumption), followed by hot water demand (17%) and appliance demand (13%) [4]. As a result, Numerous initiatives have been undertaken to decrease the energy required for space heating in residential buildings by upgrading the building envelope to minimize heat loss and improving overall thermal efficiency.

In order to organize and coordinate these initiatives and efforts toward energy efficiency in buildings, guidelines and regulations have been developed, referred to as a framework for implementing energy-saving measures. Amongst these regulations and codes, “part L: Conservation of fuel and power” and “passive house” are widely known in this scope in the UK.

Approved Document Part L specifically focuses on energy efficiency and aims to improve the thermal and energy performance of buildings by setting requirements for insulation, air tightness, heating, cooling, and lighting systems. Besides, the passive house standard is a rigorous guideline for energy efficiency developed in Germany in the late 1980s [5]. The principle behind the passive house is to create buildings that require a very small amount of energy for heating and cooling, and this is
achieved through a combination of orientation design, shading system, super insulation, triple glazed windows, and a controlled ventilation system [6].

In this regard, many studies have been conducted to evaluate the effects of implementing energy-saving measures in existing buildings and their effect on overall energy consumption. Evangelisti et al. [7] assessed the impact of applying retrofits (e.g. utilizing double-glazed windows, and adding thermal insulation to the roofs and walls) on energy performance in a building constructed during the 1950s in Rome. The result showed a reduction of up to 40% in energy consumption. A similar study by El Darwish [8], in a case study building in Egypt, showed a reduction of 33% in annual energy consumption.

Hyeon Jo et al. [9] implemented retrofits with a focus on improving openings in building envelopes by changing entrances and windows and reducing thermal bridges on the building envelope, in a case study building in South Korea, which reduced the annual energy consumption by 10 percent. Zhou et al. [10] analyzed the effect of window-to-wall ratio according to building orientation on energy consumption in a case study building in China. The results of this study revealed the relation between window-to-wall ratio in different orientations on the building’s overall energy consumption, and effectively utilizing this strategy can reduce the consumption by up to 4%.

Although applying these strategies significantly reduce energy consumption, it is important to also consider their impact on thermal comfort, particularly for vulnerable populations. Currently, in the UK, social housing accounts for approximately five million out of 28 million housing stock [11]. To achieve the best results, any effort to reduce energy consumption in residential buildings should also consider thermal comfort and indoor air quality. In this regard, many studies have been carried out to evaluate the occupants’ thermal comfort before and after implementing energy efficiency retrofit.

Kim et al. [12] assessed the effect of energy efficiency retrofit on occupants’ thermal comfort. They coupled retrofit in the building envelope with improving the HVAC system, which decreased energy demand and the percentage of dissatisfied occupants in the case study building. The same results have been achieved in other case study buildings in Germany and Sweden by Gartner et al. [13] and Liu et al. [14]. Although utilizing mechanical ventilation alongside improving the building envelope can result in lower energy consumption and better summer/winter thermal comfort, it may not be economically feasible in many cases, including in social housing [12], [15]. To this end, this study intends to assess the effects of retrofit strategies on both energy consumption and summer/winter thermal comfort in a case study building in the social housing sector of the UK.

2. Materials and Methods

A 2-bed, southwest-facing, naturally ventilated flat (Figure 2, 69 sqm) in Newham, London, UK, was selected as the case study flat. The case study building was built in 1965 and renovated during the 1990s. Simulations were conducted in IES(VE) to assess the energy performance and summer/winter thermal comfort condition in the case study building for the base case and retrofitted scenarios explained below in section 2.2.

The heating set points for the different zones of the case study flat are considered according to the “CIBSE guide A” recommended comfort criteria as follows: 18°C bedrooms and kitchen, 21.5°C halls/stairs/landings, 22.5°C living room and 21°C for bathroom [16]. These set points are linked to the occupancy profile of the zones, in which the rooms are considered to be occupied 24/7, while the living room and the kitchen are occupied from 9 am to 10 pm. The energy supply system in the building is all-electric, and the flats are heated with electric radiators. In terms of material used, the building has solid concrete walls (150mm thickness) and internal roofs/floors with double-glazed windows. The details of the current status of building elements are presented in Table 1.
For the living room, kitchen, and bedrooms, the number of hours during which \((\text{operative temperature} - \text{comfort temperature})\) \([18]\) is greater than or equal to one degree (K) shall not be more than 3 percent.

For bedrooms only: the operative temperature in the bedrooms from 10 pm to 7 am shall not exceed 26°C for more than 1 percent of annual hours.

2.1 Thermal comfort assessment

CIBSE TM59 provides a standardized method to assess the risk of overheating in naturally ventilated residential buildings during the summer period. The following criteria must pass from May to the end of September in order to avoid the risk of overheating in buildings \([17]\):

1. For the living room, kitchen, and bedrooms, the number of hours during which (operative temperature – comfort temperature) \([18]\) is greater than or equal to one degree (K) shall not be more than 3 percent.
2. For bedrooms only: the operative temperature in the bedrooms from 10 pm to 7 am shall not exceed 26°C for more than 1 percent of annual hours.

It should be noted that windows should be modeled as open when both the internal temperature exceeds 22°C, and the room is occupied. Moreover, internal doors are left open in the daytime but are assumed to be closed when occupants are sleeping. Furthermore, PMV \([19]\) is a widely used approach to assess thermal comfort in indoor environments, and it is utilized in this research to analyze the thermal comfort of occupants from October to the end of April (heated periods). This method calculates an index value on the basis of four measurable parameters (air velocity, air temperature, mean radiant temperature, and relative humidity) and two expected variables (clothing and metabolism rate). This index value ranges from +3 (indicating feeling too hot) to -3 (feeling too cold), and the thermal acceptability criterion is considered between 0.5 to -0.5 \([19]\), \([20]\). In order to conduct a simulation on IES VE, CIBSE design summer year (DSY1) and IES London city airport weather files were utilized to assess summertime overheating analysis and PMV index, respectively.

2.2 Retrofit strategies classification

Two sets of retrofit strategies, mainly focusing on improving the building fabric, air tightness, and windows’ thermal transmittance, were considered in order to meet part L of the UK building regulations and passive house requirements; and Three scenarios were considered as follows:

- Base case (current situation).
- Retrofit to Part L standards.
- Retrofit to Passive House standards.
Table 1 provides detailed information regarding the retrofit strategies in the building.

Table 1. Building characteristics before and after retrofit strategies.

<table>
<thead>
<tr>
<th>Building element</th>
<th>Passive House</th>
<th>Part L</th>
<th>Current situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall U-value (W/m2K)</td>
<td>0.15</td>
<td>0.3</td>
<td>2.2</td>
</tr>
<tr>
<td>Windows U-value (W/m2K)</td>
<td>0.77</td>
<td>1.4</td>
<td>2.29</td>
</tr>
<tr>
<td>Windows G-value</td>
<td>0.55</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Internal ceiling (W/m2K)</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>Airtightness (ACH)</td>
<td>0.05</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Roofs (W/m2K)</td>
<td>0.15</td>
<td>0.15</td>
<td>2.1</td>
</tr>
</tbody>
</table>

3. Results

This section is focused on assessing occupants’ thermal comfort in the current situation and after implementing part L and passive house retrofit strategies. Furthermore, the impact of these retrofits on energy consumption, and specifically space heating, has been quantified.

Figure 3 shows the operative temperature in the living room and bedroom from May to September to assess the risk of overheating in summer according to CIBSE TM59 guidelines. In the base scenario, the living room’s maximum operative temperature has reached 33°C, which is almost the same in part L and passive house retrofits. However, the average operative temperature is lower in the Base scenario. For example, the bedrooms’ average temperature in the Base case, part L, and passive house retrofits is around 21, 22, and 23°C, respectively.

![Figure 3. Operative temperature in (top) Living room (bottom) bedroom during May-September](image-url)
In the kitchen, where there is more internal gain due to cooking, the maximum operative
temperature reached 35°C during late July in passive house retrofit, and the average is almost 24.5°C in
both part L and passive house scenarios. Furthermore, more than 12% of hours (operative temperature – comfort temperature) is greater than or equal to one degree (K), which shows the high risk of overheating in the kitchen when applying passive house requirements to this flat. This variable is almost 2 and 3.5 percent in the base case and part L retrofit.

Overall, between four occupied zones (bedrooms, kitchen, and living room), the living room and kitchen cannot meet the CIBSE TM59 requirements in the passive house scenario. According to simulation results, the living room has passed the assessment in part L, where 1.1 percent of hours, overheating has been reported. Finally, Bedrooms are the least problematic zones, and only in less than 1 percent of hours, TM59 requirements are not met in all scenarios.

During winter, PMV index assessment shows that occupants are likely to experience a warm sensation (PMV index of around 1) in passive house retrofit (Figure 4). Passive house retrofit is recommended to be coupled with mechanical ventilation in order to supply fresh air. Although in this model, occupants will open windows when the indoor temperature reaches 25°C, applying a high level of insulation and airtightness, and relying on natural ventilation, can result in thermal discomfort during winter, as shown in Figure 4. This however needs more investigation to assess the effects of applying mechanical ventilation on energy consumption and thermal comfort.

On the other hand, the case study’s current situation does not provide a comfortable indoor condition during winter since the PMV index is less than -0.5 in 20 and 50 percent of hours during winter in the living room and bedroom, respectively. Moreover, part L retrofits show a better indoor environment in terms of thermal comfort, where the PMV index in bedrooms and living room is ranged between 0.5 and -0.5 in almost 85 percent of hours.

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**Figure 4.** PMV index in (top) Living room (bottom) bedroom from October to the end of April.
Regarding energy consumption, the case study flat consumed 155 KWh/m² before implementing retrofits, which is almost 20 percent higher than new domestic flats in the UK [21]. Around 60 percent of the energy has been consumed for space heating purposes, which matches typical UK scenarios [4]. Applying strict standards for building envelope insulations, such as Part L and passive house, can reduce energy demand for space heating by up to 90 percent in the case study. Figure 5 shows that improving exterior wall insulation and utilizing triple-glazed windows can save almost 60 percent of total annual energy consumption. Hence, as expected, applying passive house standards achieved better results decreasing total energy consumption to 63 kWh/m², which matches the monitored performance of implemented passive house buildings in the UK [22, 23].

![Figure 5. Yearly energy consumption and share of space heating.](image)

### 4. Conclusions

Almost 30 percent of energy in the UK is consumed in the domestic sector, which highlights the importance of energy efficiency measures in buildings. There are more than 5 million social housing properties, mostly occupied by vulnerable populations, that require more consideration while applying energy efficiency measures. Two sets of retrofit strategies were simulated in IES (VE) to comply with the Part L and passive house standards in a case study building to assess its performances in terms of thermal comfort and energy consumption.

The results indicate that implementing a high level of insulation and airtightness in buildings can increase the risk of overheating during the summer, particularly in zones with higher internal gain, like kitchens. Furthermore, during winter, part L retrofit resulted in a better performance, where the PMV index was between 0.5 and -0.5 in 85 percent of hours. Finally, in terms of energy consumption, there is a 60 percent energy-saving opportunity in the case study building, utilizing triple-glazed windows and exterior wall insulation. This paper purely focused on building fabric retrofit strategies by improving U-Values to the Part L and Passive House standards. Further studies are required to assess the effects of other strategies such as shading, ventilation, thermal mass, occupants’ behaviours, orientation, other weather scenarios, etc. on the energy performance and thermal comfort in the case study building.

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References


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Towards Inclusive Planning for Energy Transition in a Post-coal Future in the Hunter Valley, Australia

Extractive industries such as mining have a tremendous impact on the land, the environment, and people. Mining can define the economic and social environments of the workers and the urban areas and communities directly or indirectly impacted by the industry. The Hunter Valley has a long tradition as some intense coal mining sites have been established there since European colonization. The communities in the valley have experienced mining activities that impacted their lives and defined the valley's character closely related to energy production and export. However, the enormous environmental impact and the trends toward cleaner energy have prompted a transition stage in which 17 mines will close in the next two decades, requiring rethinking the priorities and observing the emerging opportunities for designing post-coal futures in the Hunter. This study observes the planning initiatives, the process of mine closure, and the challenges of promoting community participation. This study provides a state-of-the-art of current knowledge and approaches for designing and planning energy transition considering the multiple issues and complexities, emphasizing the social dimensions of these planning processes. Furthermore, this study presents the results of community engagement efforts conducted in the Hunter Region toward defining pathways for promoting codesigning future scenarios. The findings of this study focus on analyzing the critical issues related to inclusive and resilient communities, which will be critical in designing the future of the Hunter Valley.

Keywords
Post-mining design and planning; Inclusive planning; Hunter Valley, Australia

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1. Introduction

In the context of climate change and unpredictable multidimensional impacts that threaten the current development approaches, energy transition emerges as one of the crucial issues communities face that will define the adapting strategies at local, national, and global scales [1]. Conventionally, the discourse and policy on energy transition often dismiss the social impacts and the opportunities in favor of technological approaches to switch from fossil fuels to cleaner energy futures [1-3]. However, Feldpausch-Parker and Endres [1] claim that addressing energy transition as a socio-technological phenomenon enables a paradigm change from determining the technical feasibility of adopting cleaner energy technologies to understanding the complexities and messiness inherent to the social, political, economic, and cultural dimensions. Switching the approaches for planning and designing for energy transition allows rethinking its transformative potential arising from the coupling of social organization and energy production and consumption [4]. The planning for transformation in the context of cleaner energy futures represents a unique opportunity to reconsider development with sustainability, resilience, and equitable lenses to shape a desirable future [1-3].

Australia has a long history of coal extraction and has been crucial for its development, particularly in the estate of New South Wales (NSW). Coal extraction has enabled the development of towns and infrastructure during the twentieth century [5]. The positive image of coal in NSW was until recently prevalent in the social, cultural, economic [6] and political discourse [7]. However, Australia is finally witnessing a boost in the call for a transition to cleaner energy futures [5]. With the declining coal extraction and burning, the Hunter Valley in NSW is experiencing a transformation process with drastic changes that challenge the region’s future development. Across the valley, 17 mines will close in the following two decades, threatening tremendous social, cultural, and especially economic impacts [8]. The initiatives proposed to address the transition from a coal dominant to promote development in a post-mining future have been considered inadequate as these fail to consider that “there is far more than rebuilding the economy” [9]. The community organization Hunter Renewal claims that the transition process requires restoring and rehabilitating the landscapes while addressing the different needs and concerns from multiple angles with inclusive and participatory approaches [9]. Furthermore, diverse case studies and researchers have highlighted the importance of multidisciplinary, spatial planning and governance approaches to address energy transition and design clean energy futures [2, 10, 11].

Therefore, this study aims to analyze critical issues for inclusive planning in the context of energy transition based on the experience in the Hunter region, NSW, Australia. Thus, this paper compiles studies and case studies in an exploratory study regarding Australian and international experiences in energy transition to enable discussion for post-coal planning and design in the Hunter.

2. Materials and Methods

This paper is a state-of-the-art of current knowledge and approaches for designing and planning energy transition considering the multiple issues and complexities, emphasizing the social dimensions of these planning processes. The analysis of the literature body is intended to encourage the discussion about the post-mining future in the Hunter region. Peer review and grey literature were identified through online searching focusing on the following search terms or keywords: Mine closure, Energy transition, Energy transition in Australia, Mine closure in Australia, Energy transition in the Hunter, Mine closure in the Hunter, Planning for energy transition, Spatial and energy planning, Inclusive planning, and Participatory planning. The sources selected were analyzed through traditional literature review, also known as narrative or non-systematic literature review [12]. The narrative synthesis implies an interpretative technique to describe similarities, dissimilarities, and complementarities among the analyzed studies [13, 14]. Furthermore, by analyzing secondary data, this paper contains publicly available sources that do not require ethics approval from the University of Newcastle.
3. The Social Dimensions of Mine Closure Towards Energy Transition

Mine closure profoundly impacts local communities left in a situation of distress as the local economies struggle, especially if these are highly dependent on extractive industries [15]. Additionally, essential services and facilities such as health and education facilities can disappear if these are provided or supported by mining companies [15, 16]. The closure of mining sites is significant in the lives of individuals, families, communities, and local governments [17]. Chaloping-March [17] claims that mine closure is more than a managerial and technical engineering process within the life cycle of a mine. Mine closure extends beyond the understanding of decommissioning extractive activities in a processing plant or the physical rehabilitation of a site and landscape [16].

Bainton and Holcombe [16] argue that mine closure and the post-mining processes can stretch for years and generations, which often uncovers various conflicting interests, values, and agendas among diverse stakeholders that will have their own visions and priorities of a post-mining future. Della Bosca and Gillespie [5] observe the challenges for local communities as these often develop long-term social ties and generational links to the extractive industries with positive and negative perceptions [18]. The complexities in the community-mining relationships also include extractive industries’ valuable contribution to local identity and heritage [5]. Thus, Tschakert, Barnett [19] propose a values-based approach to climate change adaptation, which considers the loss of intangible assets such as knowledge, sense of place, social cohesion and identity.

Bainton and Holcombe [16] argue that resource development’s full costs and benefits must be accounted for to understand the social impacts of mine closure. To do so, Bainton and Holcombe [16] propose a framework considering two critical concepts that highlight the social dimensions of mine closure: procedural fairness or justice and social risks [16]. Miller, Iles and Jones [20] observe that a key aspect of energy justice is ensuring community empowerment for people to choose whether and how energy systems and the impacts on their daily lives will change. Furthermore, social risks are associated with identifying key liabilities for companies, communities, and governments. Thus, Bainton and Holcombe [16] identified five procedural and risk dimensions (see Table 1).

<table>
<thead>
<tr>
<th>Procedural dimensions</th>
<th>Risk dimensions</th>
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<tbody>
<tr>
<td>Integration and sustainability</td>
<td>Housing and town normalization</td>
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<tr>
<td>Stakeholder engagement</td>
<td>Service and infrastructure provision</td>
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<tr>
<td>Baselines, risks and impact assessment</td>
<td>Economic linkages and transitions</td>
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<td>Governance process and the state</td>
<td>Indigenous engagement in post-mining land use</td>
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<td>Local-level agreements with communities and affected land-holders</td>
<td>Cultural heritage management</td>
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3.1 Procedural dimensions

A broad body of literature refers to sustainability as a cooperative and social expectation in the wake of mine closure, which entitles the integration of closure throughout the mining cycle with feasibility and environmental impact assessments [16]. Closure planning can represent an opportunity to influence decisions, trigger improvements to the project design, and improve outcomes. However,
Integration might be challenging as it is often delayed and threatens with failing outcomes [16]. Siwik and Clemens [21] claim that the integration of impacted communities should be considered even before the mining operations promote social acceptance and support the closure as part of the mine life cycle. Understanding integration as an operational practice supports the development of internal capabilities within the relevant stakeholders and especially the communities, thus assisting the deeper ownership of mine closure plan and enabling its execution as intended [22].

Bainton and Holcombe [16] highlight stakeholders' engagement as crucial in the mine closure process and transitions for a post-mining future which requires effective communication throughout the process [23]. Everingham, Rolfe, Lechner, Kinnear, and Akbar [24] observed the existence of various criteria for engaging stakeholders, which adds complexity to the possibilities for engagement. However, the diversity in criteria also offers various opportunities for incorporating valuable perspectives, co-producing knowledge and ideas, facilitating dialogue, and fostering an open and positive future focus [24].

Risk assessments and risk management are crucial to operational management and management. However, the literature focuses on social risks narrowly addressed through company-centric approaches [16]. Instead, more attention is needed to the risks that closure may present for local communities, the impacts of these risks on operations or closure, and multiple relationships between the identified risks [16, 25]. Therefore, understanding and characterizing social risks and local forms of social capital around a mining project and using community indicators to forecast social and economic outcomes and provide ways of thinking about post-closure scenarios [16] and inform ongoing monitoring programs [26].

The existing standards, capabilities, and applicability or enforcement of policies and laws around mine closure is a contesting issue as it differs depending on the type of mining corporation, the existing policies and government capacities to enforce the law and the strategic objectives of the corporations towards the end of their operations [16]. Some corporations develop their own standards to meet broader industry norms and expectations and even manage corporate risks [16, 27]. Managing governance processes requires extensive work between governments, corporations and other stakeholders to develop the best framework based on good practices and understanding that no single jurisdiction in the world could provide an ideal model for mining closure policies [28].

The agreements between mining corporations, relevant stakeholders, and the local communities need to be done on a mutual benefit basis, considering engaging the local communities in visualizing future legacies [16]. However, the agreements reached with the local communities throughout the mine life cycle rarely address the post-mining futures [16], especially topics related to closure objectives and requirements considering social aspects. Observing the impacts and the needed relationships with social lenses evidence specific problems that are often dismissed. For instance, agreements with First Nations communities are contested as they are some of the most vulnerable groups. However, establishing agreements with aboriginal communities provides the opportunity to revisit and re-adjust the relationships established to collaborate in their desire legacy in the process of mine closure [16, 29].

### 3.2 Risk dimensions

Bainton and Holcombe [16] identified five risks (presented in Table 1) associated with mine closure and the transition to repurposing land use and energy transition from fossil fuel-based to cleaner alternatives. For instance, a common concern is the drastic reduction in population, especially in settlements and towns created near mining sites and solely intended to house mining workers or other staff dependent on mining activities. Infrastructure built for mining towns might be threatened to become useless as residents move away due to the termination of extractive activities [30]. Interestingly, in Australia, mining settlements have gradually been opened to other residents before the mine closure with the government gradually taking responsibility for critical services [16].

Despite the importance of defining the infrastructure handover left for its management, maintenance and provision of services, these are often dismissed, hindering the opportunities for post-mining sustainable economic development [16], especially in remote Australian areas [31].
Interestingly, studies on mining economy suggest that the creative responses might equally influence the legacy of the mining corporations in repurposing the infrastructure, the changes in the landscape and the remediation and rehabilitation efforts at the end of the mine life cycle [16].

The economic transition towards post-mining futures represents a major concern for local communities as the closure impacts their economic welfare and the need for a just transition [32]. Phelan and Crofts [32] reported that in communities in the Hunter Valley in NSW, Australia, the conversations around the declining coal extraction industry evidenced three priorities for the community: a) a local authority to coordinate transition efforts, b) funding for a “flagship” job-creation project, and c) more resources for technical and vocational education. Furthermore, minimizing communities’ dependency on extractive industries and diversifying the opportunities for future economic activities are increasingly part of the reclamation and repurposing alternatives proposed by planners, designers, and communities themselves [16]. For instance, repurposing mining pit lakes to promote leisure tourism in post-mining stages could minimize risks to health and habitat if they are properly remediated [33].

One of the most challenging issues in post-mining planning are the conflicts associated with the social costs for First Nations or indigenous communities which are associated with high cultural impacts. The destruction of indigenous land and their cultural heritage is an issue that is intended to increase as a study by Kemp, Owen, & Muir [34] found that 54% of mining sites intended to extract minerals for energy transition overlap indigenous land. In addition, the same study calculates that 85% of the world’s lithium reserves and resources overlap with Indigenous peoples’ lands [34]. The conflicting interests between the mining industry and First Nations cause deep wounds that are extremely complex to heal and whose legacy of destruction of sacred places, even legally done that makes the government accomplice, last well after the cease of mining operations. A prominent recent case was Rio Tinto’s destruction of the Sacred Aboriginal rock shelters at Juukan Gorge in Wester, Australia to expand an iron ore mine [35]. Therefore, it is necessary to acknowledge that in many cases, it is simply not possible to restore landscapes to their pre-mining state and that for Indigenous peoples, restoration includes complex social, economic, political, and cultural considerations [16]. The strong social and political contingent associated with post-mining futures requires paying attention to the lived experiences and aspirations of First Nation peoples who will inherit these wounded landscapes despite the best efforts that could be made in their rehabilitation [16].

Once extractive operations end, the cultural and historical value of the mining sites prompt questions about the ownership and management of these areas of sensitive heritage data collected during operations and the management of cultural heritage in a post-mining era [16]. Examples from Europe [36] and the USA [37] demonstrate how infrastructure could be repurposed and integrated into the local landscapes or create new cultural landscapes [16]. Other examples from Australia present opportunities to create memorial sites or preserve mining towns, such as Broken Hill, as active heritage cities due to their mining history [38].

4. Addressing transition in the Hunter Region clean energy futures

The Hunter is Australia’s largest regional economy, mainly dependent on primary industries such as mining, as the region holds nearly 40 percent of NSW coal deposits [8]. However, the strong influence of the coal industry in the physical, social, and economic landscapes that have shaped the region’s development is declining [9]. The fluctuations in coal prices and the global trends towards cleaner energy sources forecast a steady decrease in demand and, therefore, the need to rethink the future of the region’s socio-economic transitions. The decline of the coal
industry in the Hunter region means that 17 mining sites will cease operations in the next two decades, with the earliest Mount Arthur expected to close by 2023 [9]. Consequently, over 130,000 hectares of land will be available for new uses, including over 50,000 hectares of buffer lands and more than 25 massive voids created for open-cut coal extraction across the Hunter Valley [39].

Hunter Renewal, a local initiative observing and analyzing the energy transition in the region and serving as a platform for collaboration and engagement, claims that the post-mining transition cannot solely be based on economic development grounds, which has been the trend so far [9]. For instance, in the Hunter Regional Plan 2041, the NSW government focused on diversifying industry and employment in the region to face mine closures [40]. However, Hunter Renewal [9] claims that coordination based on government-industry meetings cannot achieve the full potential for redevelopment of the region and that this process requires the regular engagement of local communities and other relevant stakeholders. The engagement work conducted by Hunter Renewal considered five key areas. Also, based on conversations with communities and stakeholders, recommendations for each area were defined to enable the participative process of codesigning the future of the region, see Table 2.

<table>
<thead>
<tr>
<th>Key areas</th>
<th>Recommendations</th>
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| 1. Rehabilitation and Landscape Restoration  | a) Set legal obligations to prevent mine operators from leaving final voids and becoming hazards to human and environmental health  
|                                               | b) Increase penalties for failure to meet rehabilitation commitments            
|                                               | c) Establish an independent research center to develop and demonstrate best practice standards for mine rehabilitation | 
|                                               | d) Increase security bonds to cover the actual cost of rehabilitating each mine |
| 2. Regional Planning and Governance           | a) Increase coal mining royalties to fund the region’s transition and repair the landscape  
|                                               | b) Create an independent restoration commission to develop a landscape vision, coordinate restoration, and enforce best practice standards for mine rehabilitation and closure | 
|                                               | c) Use disturbed land closest to infrastructure for new industries to alleviate the impacts on local communities |
| 3. Community                                  | a) Mandate greater community involvement in post-mining land use planning  
|                                               | b) Ensure new developments benefit local communities for the long term.        
|                                               | c) Create a public information hub showing maps and details of current rehabilitation plans and progress. | 
|                                               | d) Increase funding to TAFE (technical and further education) for new courses that train local people for jobs in regenerative industries |
| 4. First Nations                              | a) Support the return of mine-owned land, especially unmined buffer lands, where sought by Traditional Owners  
|                                               | b) Engage Traditional Owners in decision-making and planning for new projects on mining lands from the outset | 
|                                               | c) Prioritise employment for local Indigenous people in land use restoration and rehabilitation projects |
| 5. Climate and Environment                    | a) Set caps on carbon emissions and water use on all current mining activities and future developments on mining lands  
|                                               | b) Establish a region-wide biodiversity corridor system that includes rehabilitated mined lands and restored buffer lands | 
|                                               | c) Prioritise the restoration of waterway ecosystems on post-mining land     |
5. Discussion and conclusions

This paper presented the issues emerging in the energy transition process in the context of mine closure that proposes transitioning from fossil fuel extraction-based development to rethinking sustainable futures. The proposed approach goes beyond the most evident economic transition to integrated approaches in which the social dimensions, impacts, and risks emerge as crucial to promote the discussion about inclusion and community engagement. Following the Bainton and Holcombe [16] proposed framework, considering procedure dimensions and risk dimensions enables the discussion of some of the main concerns for mine closure planning and understanding of the possible impacts of the decisions taken in a complex and messy planning and implementation process for post-mining development. In identifying community priorities and main concerns resulting from engagement efforts in the Hunter Region facing a process of mining decommissioning, Hunter Renewal offers an alternative perspective to the government and industry priorities [9]. The strong focus on social concerns and the necessity to engage communities and relevant stakeholders beyond the government-industry agreements echoes the Bainton and Holcombe [16] framework.

Recommendations presented in Table 1 show the communities concerns and priorities. For instance, there is a preoccupation with accountability in decommissioning the mines and the landscape left behind, whose appropriate restoration and rehabilitation must be ensured through securing financial resources, developing technical capabilities, and setting adequate standards and policies. Community engagement in decision-making is crucial, particularly concerning culturally appropriate approaches to engage First Nations or Indigenous communities. Furthermore, community engagement strategies should also encourage the development of upskilling opportunities representing the economic transition through training and retraining for active community participation in the region’s future economic development. Finally, transparency and independence are paramount in planning, designing, coordinating, and delivering post-mining future scenarios of the Hunter region and their materialization, focusing on the long term.

Based on the discussion in this paper, the complexities in the transition planning and codesign process require extensive and continuous participative work in the long term. In the case of the Hunter Region transition, one of the first mining sites to be decommissioned by 2030. This process will provide valuable lessons on what to do or what not to do, which requires developing adaptable capacities to incorporate good practices and avoid repeating failures. Furthermore, the importance of the Hunter Region, the scale of the land rehabilitation, and the economic and human impacts of the post-mining planning and implementation will become a national and global reference towards the current transition trends to cleaner energy futures.


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References


9. Hunter Renewal, After the coal rush, the clean up. A community blueprint to restore the Hunter. 2023, Hunter Renewal: Newcastle, Australia.


17. Chaloping-March, M. Business Expediency, Contingency and Socio-Political Realities—A Case of


19. Tschakert, P., et al., Climate change and loss, as if people mattered: values, places, and experiences. Wiley Interdisciplinary Reviews: Climate Change, 2017. 8(5).


