sustainability

MDPI

Article

Use of Digital Tools (Wikihouse System) in Multi-Local Social Housing

Doris Esenarro [1,*], Emerson Porras [2,3], Hardy Ventura [2], Julio Figueroa [2], Vanessa Raymundo [2,3,4] and Lorena Castañeda [2,3]

1 Faculty of Geographical, Environmental and Ecotourism Engineering, Federico Villarreal National University, San Miguel 15088, Peru
2 School of Architecture and Urban Planning, University Ricardo Palma, Santiago de Surco, Lima 15039, Peru; emerson.porras@urp.edu.pe (E.P.); hardy.ventura@urp.edu.pe (H.V.); 202112586@urp.edu.pe (V.R.); lorena.castaneda@urp.edu.pe (L.C.)
3 Research Laboratory for Formative Investigation and Architectural Innovation (LABIFIARQ), Santiago de Surco, Lima 15039, Peru
4 Institute of Built Habitat Research (INIHAC), Santiago de Surco, Lima 15039, Peru
* Correspondence: doris.esenarro@urp.edu.pe

Abstract: The primary objective of this study is to formulate a comprehensive digital and physical model, at a scaled level, for a social housing unit utilizing the open-source Wikihouse system. The construction industry is currently grappling with the dual challenges of a real estate crisis and climate change. In response to this scenario, the integration of industrialized methods in construction processes is advocated to enhance the overall quality of the end product, streamline construction timelines, and curtail production costs. The algorithm developed for this purpose leverages Rhino and Grasshopper programs, thereby optimizing material efficiency when compared to traditional individual pieces. Noteworthy among the features of the Wikihouse system is its remarkable versatility, allowing implementation in diverse locations. This flexibility stems from its efficient assembly characteristics, which liberate it from the constraints of rigid modular structures, contributing significantly to architectural design flexibility. The paramount finding of this research is the demonstrated efficiency of the proposed system, requiring 44% less time compared to conventional construction practices and exhibiting a commendable 29% reduction in costs. These outcomes position the Wikihouse-based approach as an appealing and competitive alternative within the real estate sector.

Keywords: modular; open-source; digital tools; sustainable construction; Wikihouse

Citation: Esenarro, D.; Porras, E.; Ventura, H.; Figueroa, J.; Raymundo, V.; Castañeda, L. Use of Digital Tools (Wikihouse System) in Multi-Local Social Housing. *Sustainability* **2024**, *16*, 3231. https://doi.org/10.3390/su16083231

Academic Editors: Fabrizio Zuccari, Adriano Santiangeli and Fabio Orecchini

Received: 19 November 2023
Revised: 23 January 2024
Accepted: 27 January 2024
Published: 12 April 2024

1. Introduction

The construction industry in Peru is currently immersed in a complex scenario marked by challenges stemming from the real estate crisis and climate change [1]. The main drivers of climate change are human activity and high levels of greenhouse gas emissions in the atmosphere [2]. Moreover, it is primarily attributed to the construction sector's activity [3]. It is estimated that by the year 2021, this sector will consume about 40% of the available energy worldwide, contributing to approximately one-third of global greenhouse gas emissions during the construction and operation of buildings [4,5]. Based on this, industry efforts are focused on reducing energy demand and the environmental impact of buildings, improving the design phase, and implementing energy conservation measures [6].

The real estate crisis has impacted financial stability and investment in projects, generating uncertainty in the market [7]. On the other hand, climate change presents additional challenges, as Peru experiences extreme climatic phenomena, such as floods and droughts, directly affecting the planning and execution of construction projects [8,9]. The need to adopt more sustainable and resilient practices has become imperative, with the industry facing the task of finding innovative solutions to address the real estate crisis while strengthening the resilience of constructions against the impacts of climate change in the Peruvian context [10,11]. This scenario demands integrated strategies and collaboration among various industry stakeholders to effectively address these challenges and build a more sustainable sector adapted to changing climatic conditions.

In Peru, around 10 million individuals, equivalent to approximately one-third of the total population of the country, reside in informal urban settlements characterized by a lack of essential services, such as infrastructure, public spaces, and adequate equipment, in addition to deficiencies in urban planning design [12]. This figure represents approximately half of the urban population and, in some cities in the Peruvian Amazon region, the proportion exceeds 80% [13]. It is evident that the urban population's growth and the construction rate surpass the state's capacity to develop cities, highlighting significant historical deficiencies in the urban planning process and approach [14].

In recent years, technological progress has enabled the automation of processes in various economic sectors. The construction industry has not been immune to this transformation, widely adopting digital tools in its environment. This change began in the 1990s with the introduction of CAD version 1.0 software, replacing manual methods of drawing plans. Likewise, project management has evolved, gradually incorporating collaborative work principles, displacing traditional management [15].

The use of digital tools in the field of architecture is currently necessary for their application in the development of various projects, such as digital fabrication, through a set of techniques that use machines to create physical objects directly from computational designs [16]. Therefore, promoting their application in the development of architectural concepts is sought [17]. Knowledge of these tools is essential for future interior designers and architects to engage with various techniques and technologies during their education, making it a priority to experiment with a wide variety during the teaching process [18]. This application is implemented in different systems, where the representation of complex architectural elements has been significantly improved thanks to digital tools, allowing greater precision and detail in their representation [19]. Among the most widely used modular construction systems supported by digital tools is the prefabricated system, which is a method of producing elements or parts of a construction on an industrial scale, using environmentally unfriendly materials, such as concrete, which is estimated to be responsible for 90% of CO_2 emissions in industrial processes [20]. This system prioritizes cost efficiency in design and construction, and its availability is limited to large cities and surrounding areas, excluding more remote populations where access is limited [21].

Within prefabricated systems, the PPVC steel modules (Prefabricated and Finished Volumetric Construction) stand out, which propose bioclimatic strategies, such as the installation of thermal solar collectors on the module and structural resistance at great heights; however, this system entails a cost of 21,260.00 euros for a built area of 25 m^2. Additionally, the system considers factors such as costs, labor, time, and pollution [22].

Another prefabrication system on a smaller scale, used for the development of this research, is Wikihouse. It operates with a system for the creation of plywood modules manufactured through digital technology and open-source code. Created by Alastair Parvin and Nick Ierodiaconou in 2011, they claim that this system is efficient, robust, and carbon-neutral [23]. Additionally, despite its application being limited to orthogonal geometry and the need to create new pieces to fit the design models and regulations of a specific location [24], the system has been recognized for its fundamental role in the development and execution of buildings using subtractive digital fabrication equipment [25]. Consequently, many modular projects remain in the conceptual stage due to the need for expensive licenses or permits for physical development. In this context, the presence of groups promoting the use of open-source software has facilitated cooperation and information exchange. The use of these open-source software tools has also had a positive impact on reducing license costs, contributing to the overall cost reduction of solutions [26].

On the other hand, each location has a set of requirements and design strategies for the development of a proposal. In this sense, the Wikihouse system allows mass production through the development of an algorithm created by each serving entity of the open-source system. This open-source software creation culture fosters online collaboration, the integration of diverse disciplines, the importance of practical experimentation, and informal approaches to knowledge creation, research, and innovation [27]. The research approach is based on the integration of two fundamental ideas: “coexistence” and “openness.” The purpose of this research is to delve into the relationship between these concepts and their connection to existing literature on “Global Design, Local Manufacturing” [28].

Regarding housing in Peru, it presents a series of challenges depending on the location, and often not receiving much attention when designing a proposal for optimal user comfort. In this sense, the system can develop short-term modular housing production based on parameterization that uses comfort strategies [29]. This comfort is achieved through principles that prioritize the conscious use of materials [30].

Modular developments in these systems are created through similar pieces that can be assembled into a composition. There are different types or, alternatively, if we use the theory of polyominoes, which is based on the use of the cube as the main element, we are already establishing a composition method. This is because these forms have a modular structure that allows the creation of interesting three-dimensional solid spaces [31], in addition to the implementation of mechanisms related to the use of wind turbines in architectural structures and hybrid systems to create energy conversion modules [20]. One of the benefits of using this system is its modularity, which employs a parametric design methodology that discards any form that does not fit predefined parameters and, instead, focuses on developing forms that meet those criteria. This design approach provides several advantages compared to traditional methods, which are often more linear and systematic, such as concrete and steel, which have a significant environmental impact. By reducing the time needed to create models, more time can be dedicated to exploring and experimenting with the environmental comfort challenges presented by each intervention site, leading to a higher degree of refinement in the desired shapes and designs [32]. These designs focus on enabling open-source strategies in architecture [33].

Like the systems used in different specialties, designing based on modular forms is an application that seeks to optimize and improve design in contemporary architecture, both locally and globally. It requires designers to adopt an innovative approach when addressing projects, paying special attention to the concept of pragmatism [34]. The location of a housing project using the Wikihouse system has the necessary potential to meet the physical needs and conditioning requirements of the user according to the environment and climate of its location. In terms of housing typology, due to its flexibility, it can offer greater possibilities for design strategies and can adapt and leverage different ecosystems [35].

The application of digital tools, such as the Wikihouse system, in multi-local social housing has significant relevance for addressing and reducing the housing crisis in Peru. The use of digital technologies in the design and construction of houses allows greater efficiency in processes, which can result in faster and more affordable production of housing units. The Wikihouse system, being an open-source platform that facilitates digital manufacturing and the construction of modular homes, offers the possibility of adapting and customizing designs to the specific needs of marginalized and low-income communities [36,37]. The implementation of these digital tools in multi-local social housing not only streamlines the construction process but can also contribute to cost reduction, making housing more accessible for populations facing economic difficulties [38]. Furthermore, the flexibility and adaptability of the Wikihouse system allow greater versatility in housing construction that adjusts to the specific conditions of informal settlements, thus contributing to improving the quality of life of communities affected by the housing crisis in the country.

Some benefits provided by digital manufacturing include adaptability or easier implementation in different contexts due to the modular design, and the ability to be built with materials accessible worldwide, such as phenolic plywood.

- It does not require specialized labor for construction, nor sophisticated tools.
- Connection are made through snap fits without the need for additional fasteners such as nails or screws.
- It is easy to transport and compatible with any type of foundation.
- In addition to generating fewer emissions in its production than other materials, wood actually captures and stores carbon from the atmosphere while in use; this is why it is called carbon-negative.
- On the other hand, its design considers a 30 cm space for thermal insulation that can be used depending on the climatic conditions of the proposed location.

The socio-environmental benefits derived from the use of parametric design tools, software-based artificial intelligence, specifically with tools like Grasshopper and the Wikihouse system, are diverse. Software-based artificial intelligence, like Grasshopper 1.0.0007, significantly improves design efficiency, allowing faster and more accurate planning of architectural projects. The software contributes to the optimization of designs, reducing the use of materials in the manufacturing of modular parts. This has a direct impact on resource conservation and the mitigation of material shortages. The Wikihouse system stands out for using eco-friendly materials, such as wood. This not only contributes to environmental sustainability but also creates a favorable environment for the surroundings and users. The implementation of technologies like Grasshopper and systems like Wikihouse can reduce energy consumption in construction, thus contributing to energy efficiency and the reduction of environmental impact. The efficiency in design and manufacturing, facilitated by artificial intelligence parametric desing tools like Grasshopperand the Wikihouse system, leads to a reduction in costs associated with material manufacturing and processing, making architectural projects more economically accessible.

Research on the use of the Wikihouse digital tool in social housing can open various directions and future applications. Here are some possible areas that could be explored as a continuation of the research:

- Design Optimization: Investigate ways to further optimize the design of houses using Wikihouse, considering aspects such as energy efficiency, adaptability to different climates, and ergonomics.
- Long-Term Social and Community Impact: Evaluate the long-term social and community impact of houses built with Wikihouse. This could include studies on resident satisfaction, community strengthening, and the impact on social mobility.
- Sustainability and Innovative Materials: Explore additional options to improve the sustainability of the Wikihouse system, such as integrating innovative and eco-friendly materials, as well as the possibility of material recycling.

These future directions and applications can contribute to expanding the understanding and positive impact of Wikihouse implementation in the field of social housing, addressing specific challenges and leveraging opportunities for further improvement of efficiency, sustainability, and accessibility in affordable housing construction.

Based on recent advances in parametric design and digital manufacturing tools, Wikihouse and OSE Microhouse projects seek to create sustainable, efficient, and self-sufficient construction structures. They also employ various technologies for the construction of their main components [39]. These constructions incorporate a modular design that enables the creation of spaces tailored to user needs and the specific climatic conditions of their location. Versatility lies in their ability to rotate freely without compromising functionality, meaning that the only limitation to using the system in different places and achieving adaptation to the environment lies in the dimensions of the available land [39].

The positive impact of open-source software on reducing license costs is clearly demonstrated in the context of WikiHouse, an innovative platform in the field of architecture and construction. Distancing itself from traditional proprietary software with high license costs, WikiHouse adopts an open and collaborative model, which not only makes design and construction more accessible but also significantly reduces overall project costs. Building a 44 m^2 house with WikiHouse and second-hand materials can cost approximately

38,000 euros, much less than traditional methods. This cost efficiency is largely due to the elimination of design software license expenses, allowing for a better distribution of the budget for quality materials and energy efficiency [40]. Moreover, WikiHouse encourages a culture of collaboration and knowledge-sharing in the design and construction community. Users can adapt designs to their needs and share their modifications, thus promoting continuous innovation and improvements in designs. This practice not only accelerates the development of more efficient and sustainable solutions but also builds a community of practice where knowledge and experiences are freely shared.

Another study complements this view, showing how visual algorithmic modeling in Grasshopper applied to WikiHouse can generate a wide range of spatial and formal solutions, thereby expanding design possibilities and applications in temporary and modular architecture. Finally, WikiHouse has a positive impact on sustainability and energy efficiency, reducing the carbon footprint and energy consumption compared to conventional construction systems [41].

In summary, the aim of this research is to put forth the design of a housing prototype employing modular techniques and the open-source Wikihouse system. This encompasses a consideration of economic variables and user comfort through the implementation of design strategies and algorithms utilizing digital tools.

2. Materials and Methods

2.1. Methodological Phase

This research has an experimental nature. It begins with the compilation of information from scientific articles, followed by the identification of data related to the topic and its proper classification. Finally, it allows for the conduct of experimental tests, both physical and digital, of a proposal that meets the desired objective.

The algorithm played a crucial role in optimizing the efficiency of material usage. One of its specific functions was the intelligent organization of cutting pieces, achieved through an advanced 'nesting' process. Nesting is a computational technique used to arrange two-dimensional shapes in a limited space, in this case the material surface, in a way that minimizes waste. This approach is particularly relevant in the context of WikiHouse, where component information is provided in 3D and 2D formats.

Adapting this information for CNC laser cutting instead of CNC routers was a significant challenge. It required not only readjusting the dimensions and arrangement of pieces but also optimizing the cutting process for a different type of machine. The adjustable parameters of the algorithm allowed for modification of design information, from geometry to specific details for physical prototype production.

The algorithm not only maximized material utilization through effective nesting but also provided flexibility in parameter adjustments. This allowed adaptation of the design for different types of machinery and materials, thereby increasing project efficiency and sustainability. Material waste reduction is not only economically advantageous but also contributes to a more sustainable and environmentally conscious design practice. Additionally, the ability to quickly adapt the design to different production methods demonstrates the versatility and power of the algorithmic approach in digital manufacturing and architectural design.

Figure 1 presents each phase developed throughout the research process, from the selection of the modular system to the creation of a scale model. The aim of this model is to verify economic feasibility and assess efficiency in terms of user comfort. The phases include:

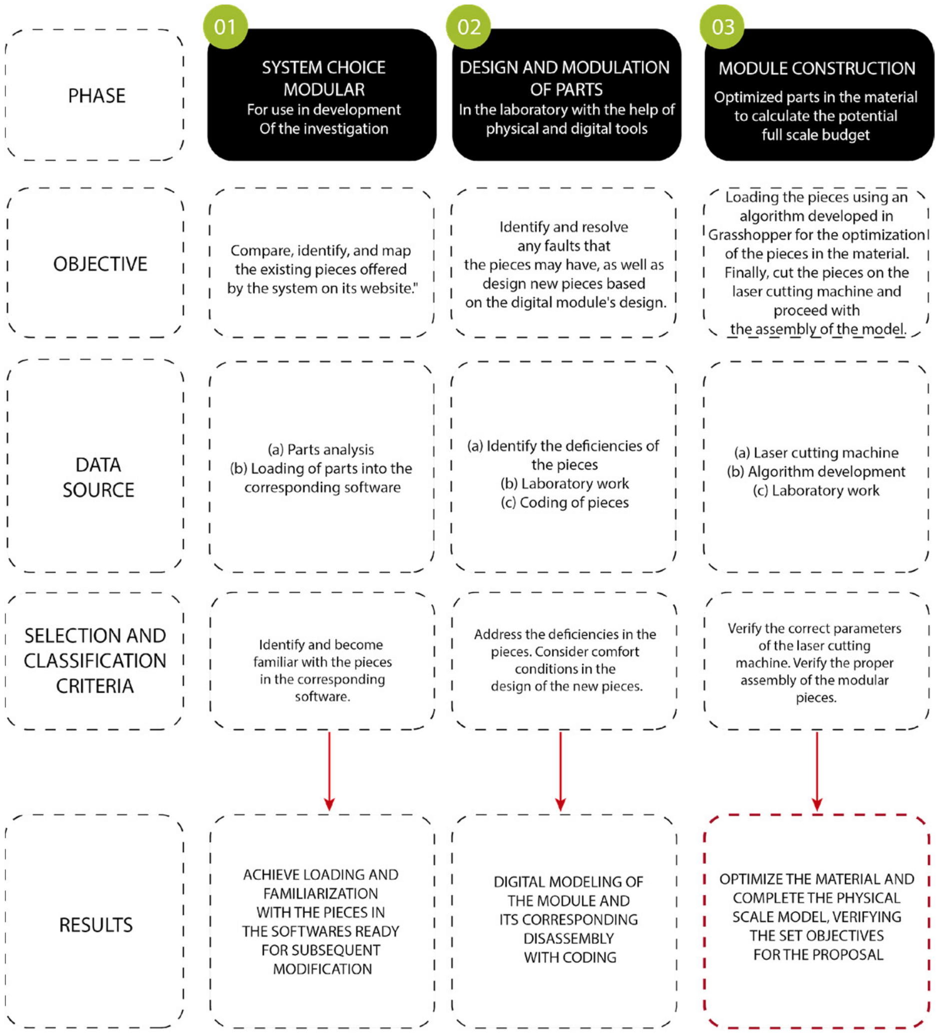


Figure 1. Methodological phase.

- Phase 1: Selection of the Modular System. The process began with an analysis to select various modular systems. During this evaluation, various factors were considered, such as software compatibility with the system, costs and materials needed for construction, circular economy considerations, and the environmental impact associated with the research outcome. The chosen system for the research was Wikihouse. To implement this, a detailed analysis of its components (piece connection model and assembly order for an orderly assembly) was conducted, along with familiarization with them, and then loading and modifying these pieces in the corresponding software.
- Phase 2: Design and Modulation of Pieces. In this stage, the search for the ideal location to develop the proposal started. This location had to meet specific criteria, such as varied climatic conditions, geographical isolation limiting access to conventional construction materials, and the availability of wood as the main raw material for the Wikihouse system. Simultaneously, progress was made in designing the housing model, incorporating new pieces. These not only met the rigorous structural standards of the Wikihouse system but also aimed at generating and developing environmental strategies that preserve the use of materials and benefit the user. These strategies were conceived to be comprehensively utilized in the module based on the final algorithm of the project.
- Phase 3: Construction of the Module. In this final phase, an algorithm was designed to facilitate the loading of the final pieces, which played a crucial role in both the laser cutting process and the construction of the physical model at scale. This algorithm

was developed using Rhino and Grasshopper programs, which sorted and categorized modular pieces, considering indicators such as area, piece shape, and scale, achieving notable efficiency in material utilization. Additionally, an estimated projection of both the required material quantity and the associated cost for the construction of the real-scale housing module was generated. The housing prototype will be made using wood due to multiple factors, such as availability and accessibility, as wood is a common and accessible construction material in many regions worldwide. This facilitates its acquisition for self-construction projects in different places, due to its lightness and ease of handling, as it is a lightweight material compared to others. like concrete or steel. This characteristic facilitates its manipulation during construction, especially in projects where active participation of individuals building their own homes is sought. Sustainability: If sustainably sourced from managed forests, wood contributes to the project's sustainability. Wood is a renewable resource, and its proper use can help reduce the ecological footprint of construction. Ease of cutting and assembly: Wood is a material that can be cut and worked with common tools, facilitating its use in self-construction projects where specialized construction skills are not required. Energy efficiency: Wood has natural thermal insulation properties, which can contribute to the energy efficiency of homes built with this material. Flexibility and design versatility: Wood is a versatile material that can adapt to various architectural designs.

2.2. Ubication

The location for the social housing prototype with the Wikihouse system was selected considering different ecosystems in the environment and the economic and social needs that the analyzed location may have [42]. Figure 2 shows the place designated for the development of the prototype was:

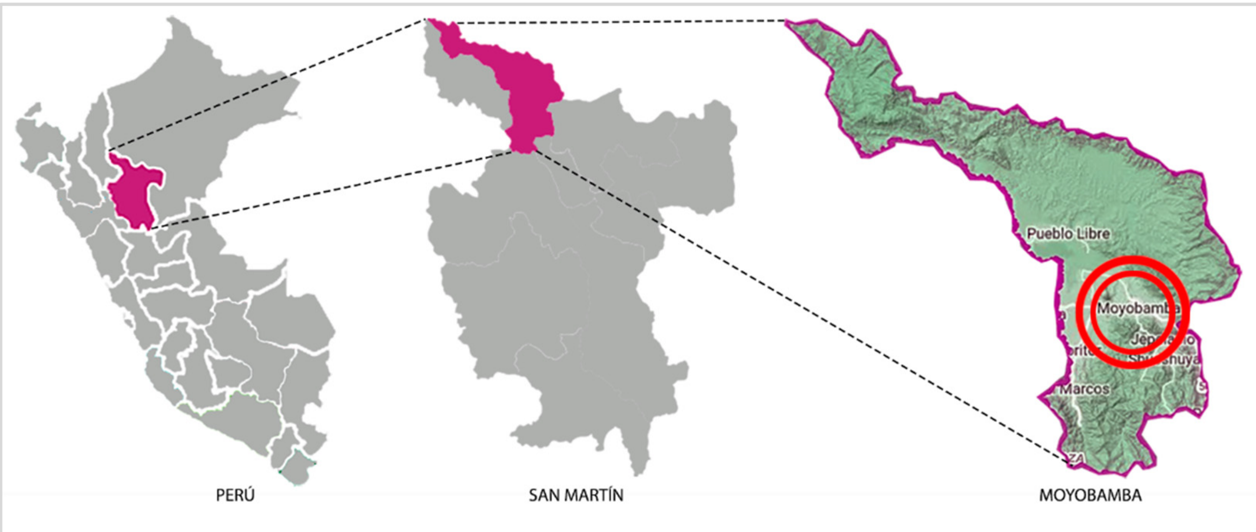


Figure 2. Place of study.

2.3. Climate

The city has a warm climate, moderately rainy with moderate temperature fluctuations. In the case of the solar chart analysis, it was found that the azimuth angle 294.6° and the elevation angle 13.91° indicate that the sunlight has a steeper slope [43].

Figure 3 represents the incidence of the solar path on the modular housing, taking into account the immediate surroundings.

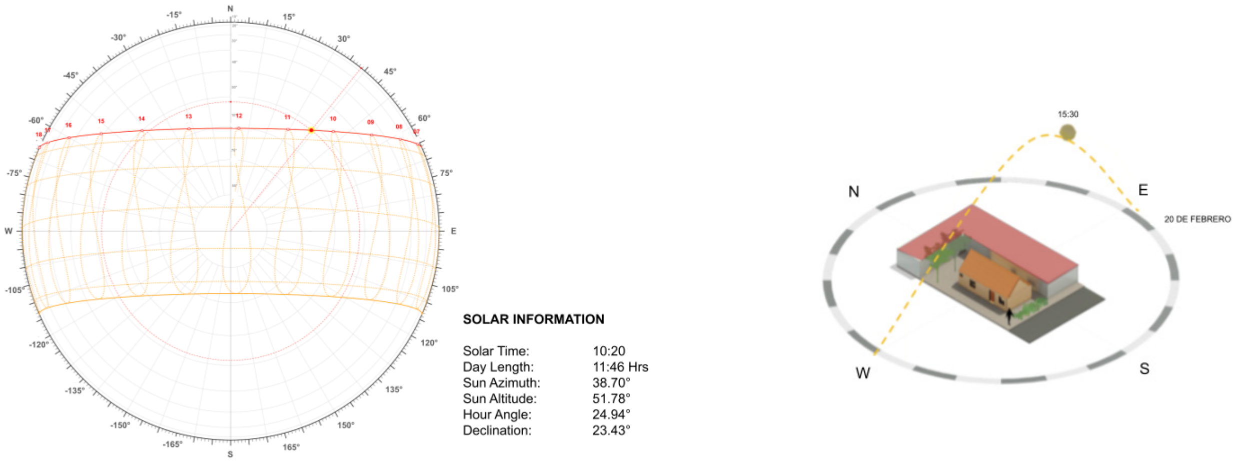
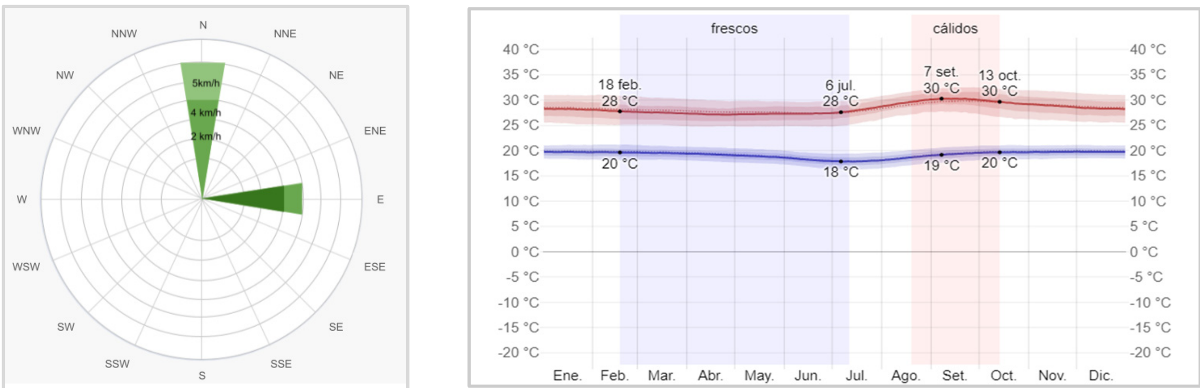


Figure 3. Solar chart of the city of Moyobamba.

2.4. Winds and Temperature

The average wind speed per hour in Moyobamba does not vary considerably throughout the year and stays within a range of approximately 0.3–4.4 km per hour. The predominant wind direction in this region most frequently comes from the east for 5.9 months, from 1 April to 28 September, with a maximum percentage of 53% on 1 August. The wind most frequently comes from the north for 6.1 months, from 28 September to 1 April, with a maximum percentage of 64% on 1 January [22] (Figure 4a).



(**a**) (**b**)

Figure 4. Wind Chart (**a**) and Temperature Chart (**b**).

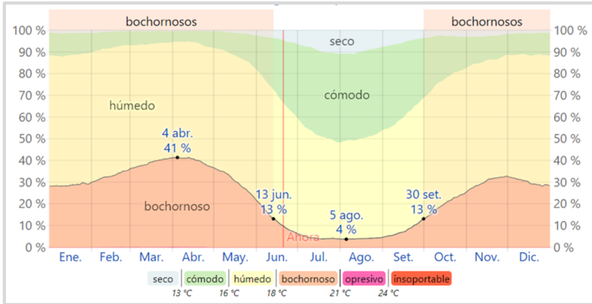
The cool season lasts 4.8 months, from 18 February to 11 July, and the average daily maximum temperature is below 28 °C. The coldest month of the year in Moyobamba is June, with an average minimum temperature of 18 °C and a maximum of 27 °C [42] (Figure 4b).

Figure 4 identifies image (a), which represents the incidence of winds in the study area with an average speed of 5 km/h. Furthermore, image (b) shows the maximum and minimum temperatures, which vary between 18 ºC and 30 ºC depending on the month.

2.5. Precipitation and Humidity

The rainiest season lasts for 7.6 months, from 29 September to 15 May, with a probability greater than 29% of any given day being rainy. The month with the rainiest days in Moyobamba is March, with an average of 13.0 days with at least 1 mm of precipitation [42] (Figure 5a).

(**a**)



(**b**)

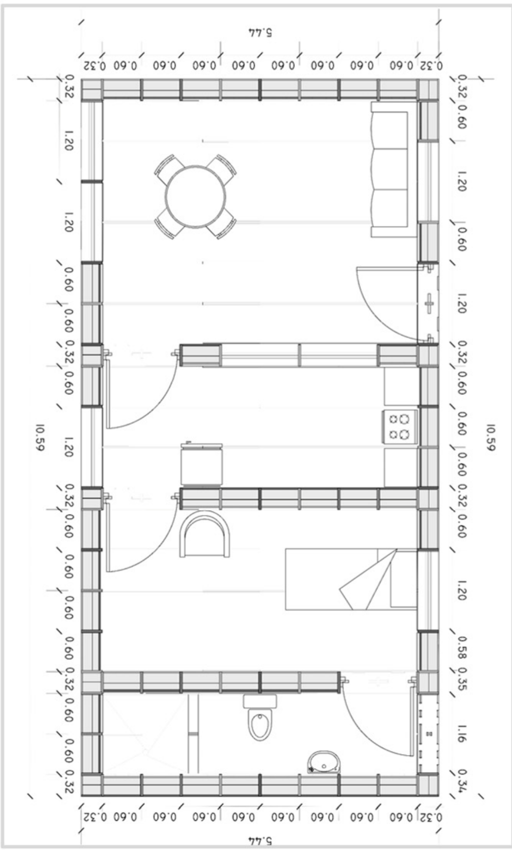
Figure 5. Precipitation Chart (**a**) and Humidity Chart (**b**).

The wettest period of the year lasts for 8.4 months, from 30 September to 13 June, and during that time the comfort level is sultry, oppressive, or unbearable for at least 13% of the time. The month with the sultriest days in Moyobamba is March, with 12.1 sultry days or worse [42] (Figure 5b).

3. Results

3.1. Proposal

The digital proposal for the modular housing prototype through the Wikihouse system incorporates a space distribution adapted to the system and the spatiality intended to be achieved (Figure 6).



(**a**)

(**b**)

Figure 6. Plan of the module (**a**) and Render (**b**).

3.2. Climate Indicators

Rooms with only one window will have poor ventilation. In this case, designs are proposed with spaces adequately ventilated through cross-ventilation, promoting the circulation of fresh air from doors or windows on opposite sides to enhance user comfort [44] (Figure 7).

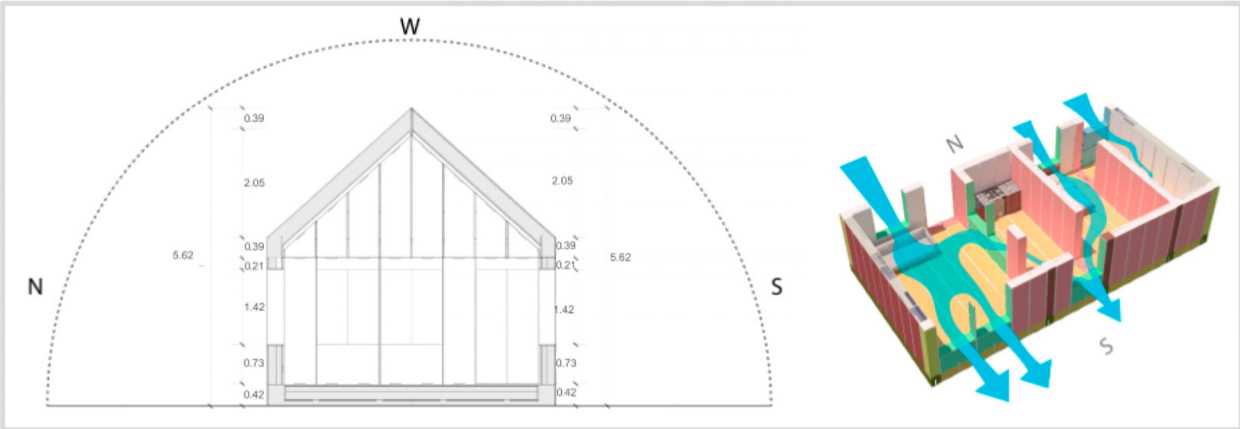


Figure 7. Cross ventilation diagram in the modular house.

3.3. Economics Indicators

The 57.50 m^2 house consists of a series of modular pieces (Figure 8), which, when joined together, create the basic spaces for a home (living–dining area, kitchen, one bedroom, and a bathroom). The aim is to benefit the users and their immediate environment in various aspects, such as comfort, economy, simplicity, etc. [45].

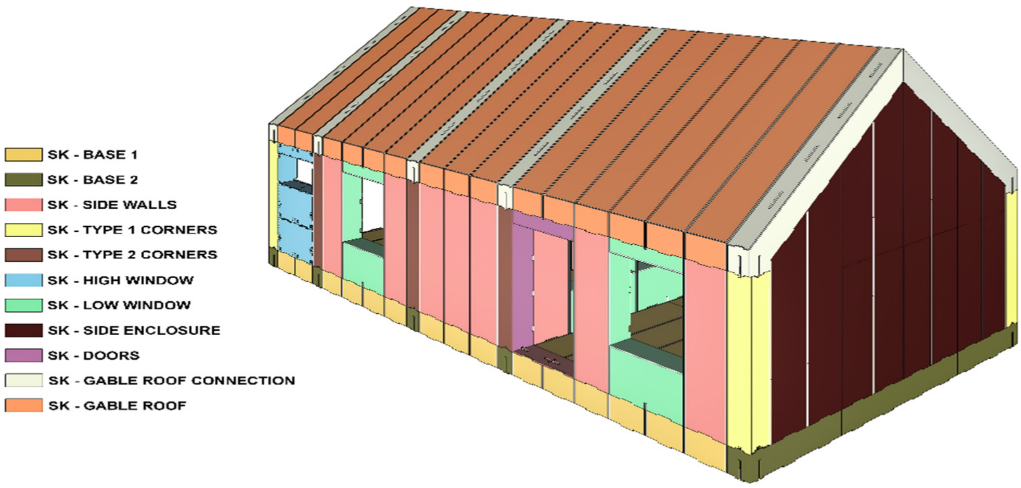


Figure 8. Identification of modular pieces in the model.

Figure 8 represents the identification of all modular components of the house.

Development with modular structures offers the advantage of adapting to user needs, and using wood, compared to materials commonly used in the area, such as steel or concrete, promotes greater integration of the circular economy, reducing environmental impacts, lowering energy consumption, and reducing the use of natural resources. Additionally, it allows for the restoration of natural capital and encourages regeneration for future reuse, bringing about a comprehensive change in construction design.

An inventory of the necessary pieces is prepared (Figure 9) for loading into the corresponding software, allowing for the determination of the material required for each corresponding modular piece number.

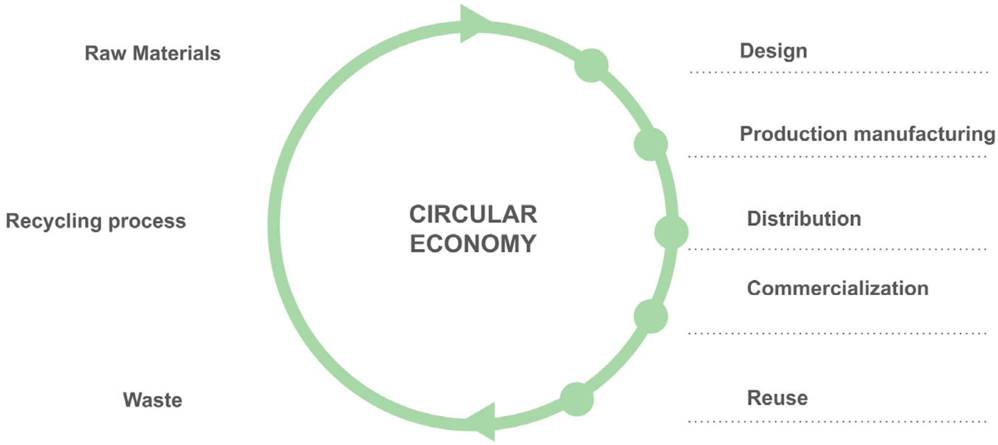
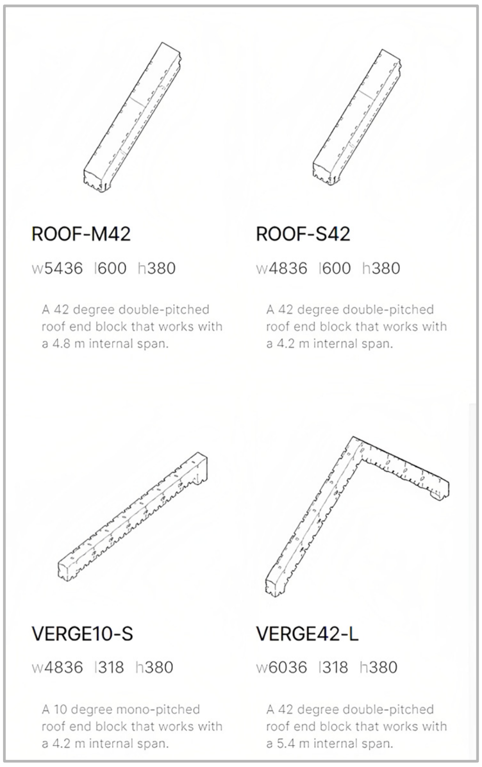


Figure 9. Identification of the modular pieces in the model.

In Figure 10, the breakdown of in-house manufacturing (b) is assessed and presented in relation to the pieces provided by the Wikihouse system (a).

NAME	Nº PARTS
SK-BASE 1	15
SK-BASE 2	5
SK-SIDE WALLS	29
SK-TYPE CORNER 1	4
SK-TYPE CORNER 2	6
SK-HIGH WINDOW (OWN DESIGN)	7
SK-LOW WINDOW	1
SK-SIDE CLOSURE	16
SK-DOORS	4
SK-CONEXIÓN TECHO A DOS AGUAS	5
SK-GABLE ROOF	15

(**a**)



(**b**)

Figure 10. Number of modular pieces by type (**a**) Modular pieces; (**b**) Source: Wikihouse.

Figure 11 presents the final algorithm, which allows for the modification of indicators, such as scale, material dimensions, margin of error, minimum separation between pieces, laser cutting machine factor, etc. All these indicators enable the proper optimization of the pieces in relation to the laser cutting material. The algorithm is divided into seven development phases, which are as follows:

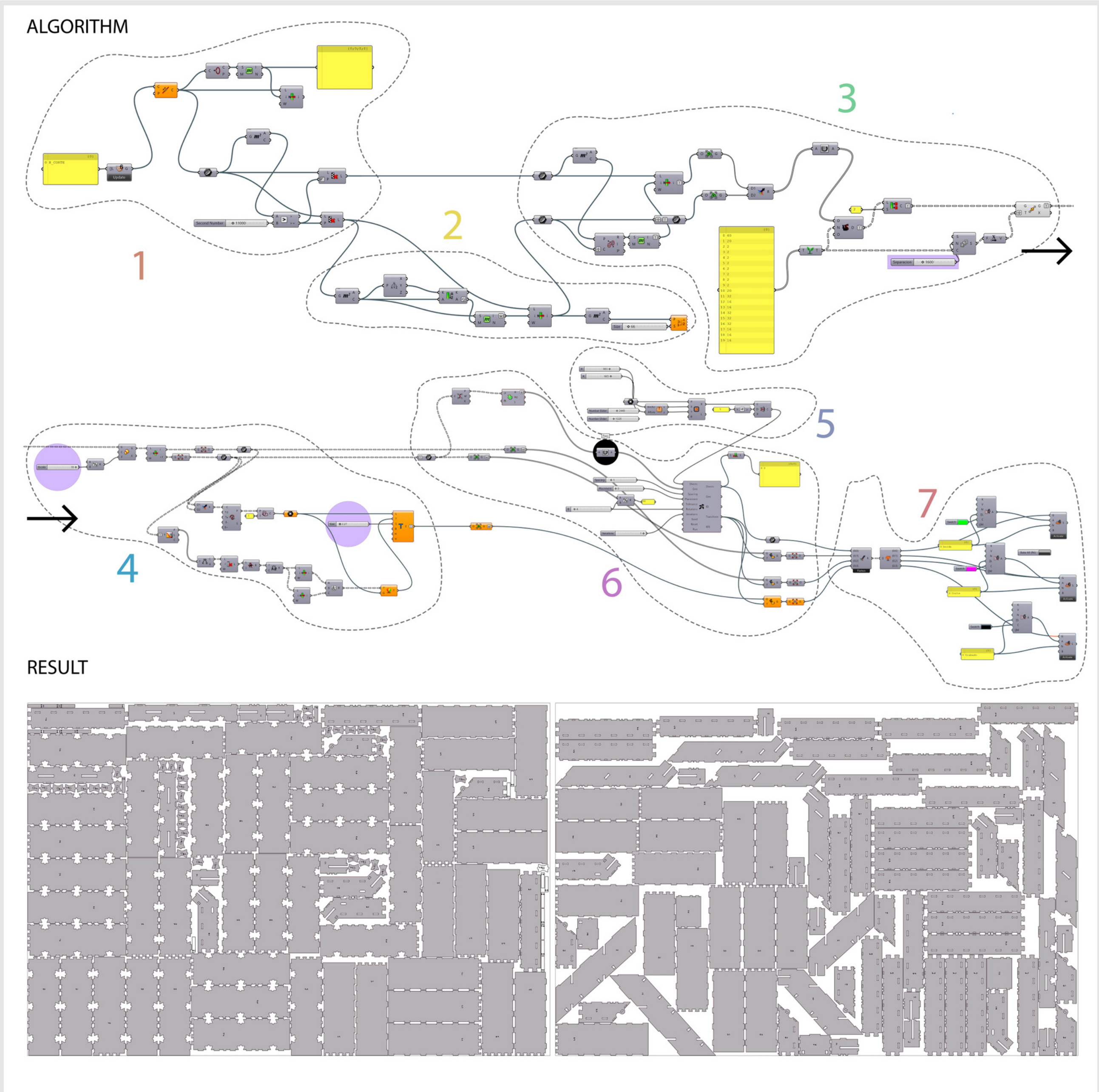


Figure 11. Graph of the use of the algorithm in the modular pieces of SK-TECHO A DOS AGUAS at a 1/10 scale on a 2 mm cardboard model measuring 965 × 665 mm.

Figure 12 represents Phase 1 of the algorithm, which allows for identification of the geometry of the modular pieces using the Elefront R6 plugin (a). After that, the area of each piece is calculated (b), and the external pieces are separated based on the area (c).

Figure 13 represents Phase 2 of the algorithm, which systematically identifies the areas of each piece and arranges them in ascending order from smaller to larger area.

Figure 14 represents Phase 3 of the algorithm where, once the pieces are identified by their areas, the respective quantity needed for each piece is indicated (a), using the cutting plan table as a reference.

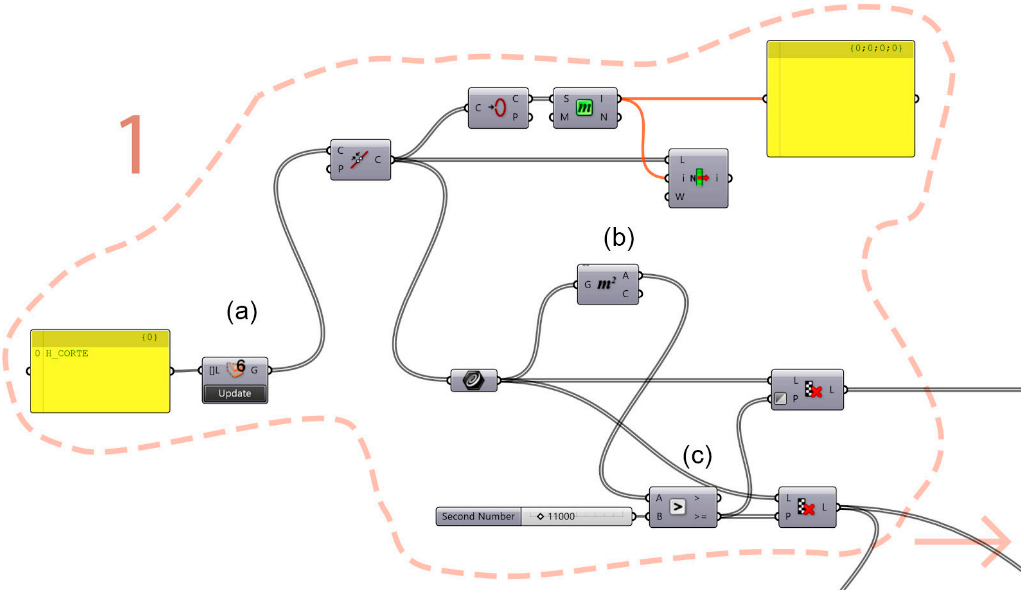


Figure 12. Phase 1 of the development of the algorithm for optimizing modular pieces in laser cutting material.

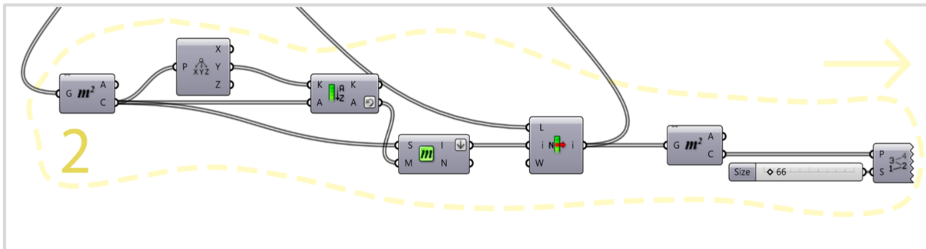


Figure 13. Phase 2 of the development of the algorithm for optimizing modular pieces in laser cutting material.

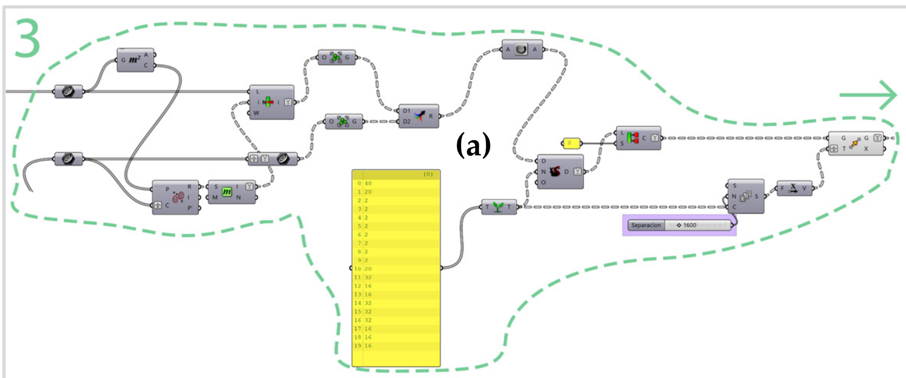


Figure 14. Phase 3 of the development of the algorithm for optimizing modular pieces in laser cutting material.

Figure 15 represents Phase 4 of the algorithm, where the scale is established for each piece (a). Subsequently, each piece is assigned a code in an orderly manner (b), facilitating the assembly of the model.

Figure 16 shows Phase 5 of the algorithm where the material dimensions are loaded (a), ensuring it does not exceed the maximum dimensions of 1300 × 900 mm accepted by the laser cutting machine. Additionally, a margin of material utilization at the edges is established, expressed in millimeters (b).

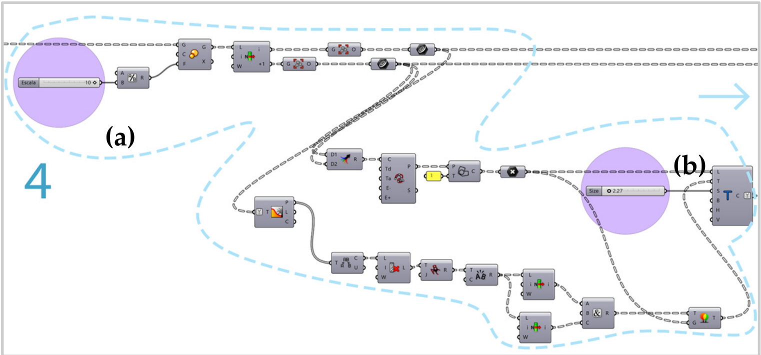


Figure 15. Phase 4 of the development of the algorithm for optimizing modular pieces in laser cutting material.

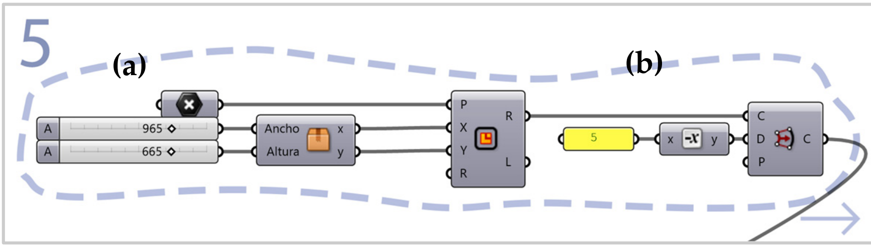


Figure 16. Phase 5 of the development of the algorithm for optimizing modular pieces in laser cutting material.

Figure 17 represents Phase 6 of the algorithm, where all the previous phases are loaded, allowing us to see the final result of the algorithm. The plugin used for this phase is Open Nest (a), which allows us to group all the previous actions. Some of the main actions of the plugin include organizing the pieces in the workspace according to their area and using them to arrange the codes of each piece.

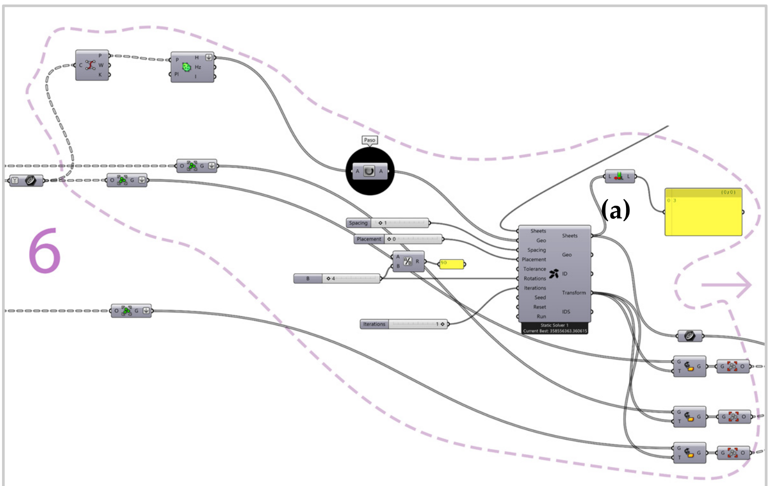


Figure 17. Phase 6 of the development of the algorithm for optimizing modular pieces in laser cutting material.

Figure 18 represents the new layers assigned for laser cutting, identified by cut lines (a), engraving lines (b), and material edges (c).

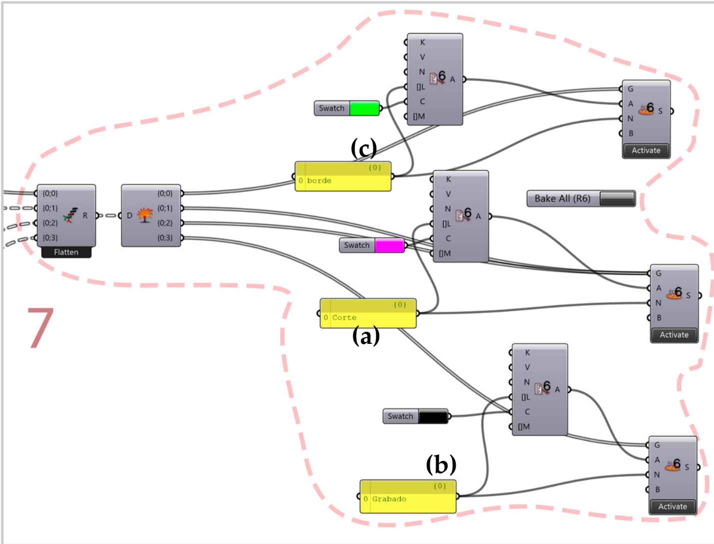


Figure 18. Phase 7 of the development of the algorithm for optimizing modular pieces in laser cutting material.

3.4. Use of the Material

To verify the efficiency of the algorithm, another algorithm is developed that allows us to calculate the material usage efficiency based on the pieces arranged by the previous algorithm (Figure 19).

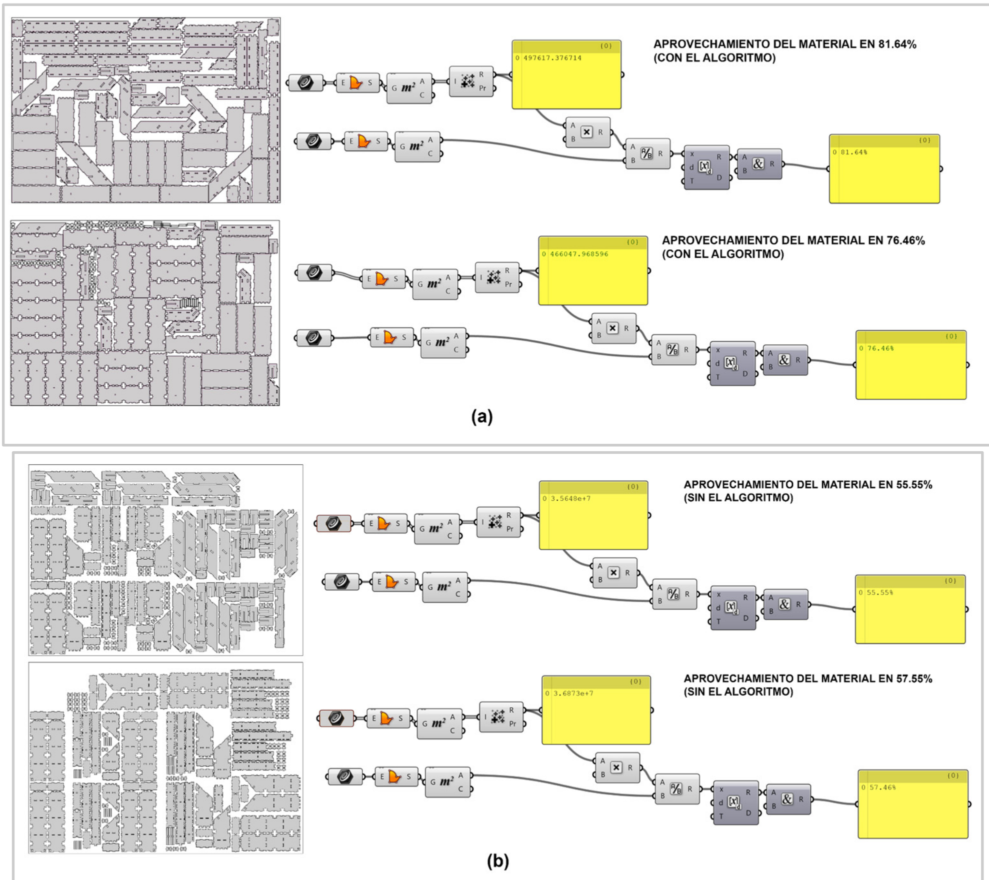


Figure 19. Chart of the material usage optimization algorithm.

Figure 19 shows the comparison of two models of arrangement for the modular pieces. In the Figure 19a, the pieces were arranged using the algorithm with a processing time of 5 min. In the Figure 19b, the pieces were arranged manually, taking 30 to 45 min to place them in the most suitable way on the material, with the possibility of making errors in the quantity of pieces required per module due to the manual process.

The final result of the algorithm in terms of material utilization demonstrated a 20% higher efficiency compared to performing the same process manually. Additionally, the use of the algorithm significantly reduces the time needed to organize and code the pieces.

3.5. Model

With the development of the physical 1/10 scale module (Figure 19), the effectiveness of the algorithm for all modular pieces required for the module was verified. Additionally, economic savings were also confirmed.

Figure 20 represents the final model of the prototype. Regarding the final model costs, for its assembly, 25 sheets of material were used (Figure 18) with a total cost of S/.325.00, where, in most cases, the pieces were manually placed without the use of an algorithm. Subsequently, all the pieces were loaded onto the material using the algorithm, resulting in a material utilization of 18 sheets with a total cost of S/.234.00, representing a cost savings of 28% compared to manually ordering and coding everything.

Figure 20. Physical model in 1/10 scale of the modular house.

4. Discussion

In the realm of multi-local social housing construction, prefabricated steel module systems, known as PPVC (Prefabricated Prefinished Volumetric Construction), have emerged as an alternative, addressing both bioclimatic aspects and structural resistance, especially in high-altitude contexts. However, limitations in these systems have been identified, mainly related to the connection between volumetric modules and the loads generated by their own weight. Although techniques and methods exist for the construction of medium and high-rise buildings [22], the need to improve flexibility and adaptability persists. In this context, this article highlights the use of the WikiHouse system as an innovative digital tool that overcomes the aforementioned limitations.

The WikiHouse system features impeccable modular design, allowing the relocation of doors and windows, as well as the efficient alteration of the design and model, adapting to the specific conditions of each location. The results obtained during the assembly process demonstrate the inherent efficiency of the WikiHouse system [46]. The ability to maintain structural unity while exhibiting flexibility for various design needs highlights the versatility and adaptability that this digital tool brings to the field of multi-local social housing construction.

The WikiHouse system aligns comprehensively with long-term social, economic, and environmental sustainability [47], specifically with circularity principles in the realm of housing construction [48]. Through its innovative design and construction approach, WikiHouse incorporates key aspects of the circular economy by prioritizing resource efficiency, reuse, and adaptability. The inclusion of new pieces in the housing model not only meets rigorous structural standards but also strategically aligns with circular economy principles. In this regard, the use of wood in WikiHouse stands out as a renewable resource with lower environmental impact, which, when employed, would reduce carbon emissions. Therefore, it is essential to consider greenhouse gas emissions in the construction sector from the perspective of life cycle analysis, which would help overcome barriers to implementing the circular economy in construction [49].

The use of wood in WikiHouse not only promotes sustainability, due to its lower CO_2 emission rate and reduced environmental impact compared to steel or aluminum [50], but also contributes to mitigating climate change. Wood products serve as a carbon storage depot and can replace environmentally harmful sources of materials and energy, such as fossil fuels. These incentives to increase the use of wood products (Harvested Wood Products, HWP) are implicit in the Kyoto Protocol, as substituting fossil fuels with wood-based fuels and energy-intensive materials with wood-based products is a means to reduce carbon dioxide emissions [51]. Additionally, at the end of their lifespan, wood components in the WikiHouse system can be reused or recycled, reducing waste compared to conventional construction and demolition methods. The modular design of the WikiHouse system also stands out, enabling efficient construction and minimizing material waste. Precision in CNC (Computer Numerical Control) cutting ensures optimal utilization of each piece, essential for sustainable resource management.

In Figure 21, the different phases of the circular economy model implemented by WikiHouse are presented, prioritizing efficiency in resource use, reuse, and adaptability.

Figure 21. Diagram of the circular economy model implemented by WikiHouse.

The application of polyomino theory in architectural development has introduced a modular composition that demands a base measure to facilitate space organization [52]. However, the use of these spatial modules becomes less flexible when faced with the task of generating irregular environments. In contrast, the WikiHouse system offers the flexibility needed for the creation of unrestricted spaces, without being limited to a rigid or strict modular structure, as well as ease of implementation in various locations due to its efficient assembly feature, enabling a diversity of shapes in its composition.

Figure 22 highlights the system's flexibility in adapting and adding new spaces over time, according to the specific needs of the user.

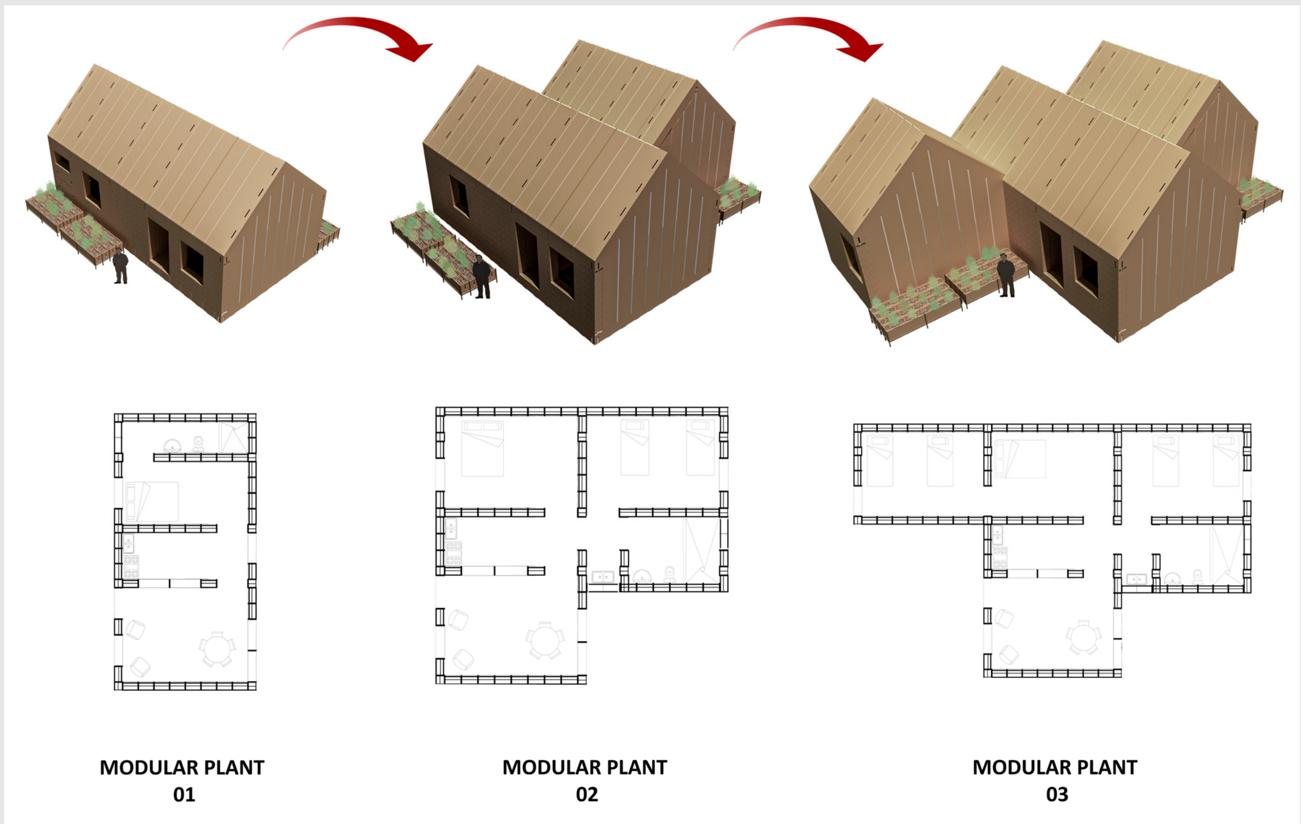


Figure 22. Chart of modifications to the base module.

In the realm of steel structural design, its properties, promoting durability, strength, and adaptability to various physical needs stand out. Despite the numerous virtues of steel, manufacturing components for structures in this material involves higher energy consumption. The main contributors to CO_2 emissions in buildings with steel structures are attributed to 52% for the production of steel beams, with the production of these structures being the primary factor in energy consumption. Additionally, since manufacturing is performed in specialized areas, the transportation of elements and tools is part of the total energy consumption [22]. On the other hand, the use of wood in architectural design offers greater adaptability, strength, flexibility, and comfort for users, making it a versatile material for application in different environments, as mentioned in previous paragraphs. Thus, in Table 1, it is shown that a steel housing prototype has significantly higher costs due to the amount of energy and the quantity of materials used in its manufacturing. In contrast, in the case of construction with wood, this stands out as the lower-cost option, besides being in harmony with its surroundings.

Table 1. Comparison of steel and wood housing prototypes: Cost and material life cycle.

Housing Prototypes	Material Cost	Material Quantity	Material Life Cycle
Steel Housing Prototype Case	850 EUR/m^2	Indefinite As it is a manufactured material, it has a greater possibility of using	Transport 19%
Wooden Housing Prototype Case	230 USD/m^2	Enough It is regenerated from the circular economy	Transport 5%

In a community in the Negev Desert in Australia, a methodology was developed to create a temporary mobile infrastructure with the assistance of the community [28]. However, this cannot be adapted to other parts of the territory because it is a closed-source system. In contrast, the open-source nature of WikiHouse contributes significantly to its adaptability and widespread use due to its collaborative development. Being open-source allows a community of developers, architects, and enthusiasts to collaborate on the continuous improvement and refinement of WikiHouse. This collective effort brings diverse perspectives and knowledge, enhancing the system's adaptability to various needs and contexts.

The tentative documentation of an emerging production prototype known as "global design, local manufacturing" or "DGML" [53] has demonstrated the innovative capabilities of commons as an alternative route for technological development in response to social needs [54,55]. Constant research into this alternative social perspective could reveal new opportunities to explore and apply practices that drive more equitable and sustainable innovation, thus improving the ability to more effectively meet social needs and address global challenges, such as the climate crisis.

In the context of homes for low-income individuals, quality of life [33] is significantly affected by bioclimatic concepts, with natural ventilation management being a key component following a low-cost approach [34]. In the proposal presented in this article, cross-ventilation is implemented in main spaces as an integral part of this bioclimatic strategy.

This research has thoroughly explored the impact and implications of implementing the WikiHouse system in the context of multi-local social housing construction. Through the evaluation of its versatility, sustainability, and adaptability, its crucial role in addressing identified limitations in other prefabricated systems has been highlighted. The versatility of WikiHouse has been demonstrated in its ability to efficiently alter the design, adapting to specific conditions of each location. This distinctive feature, supported by the ongoing collaboration of the developer and architect community, as well as the open-source approach, underscores the transformative potential of commons-based practices and collaborative innovation. From a sustainability perspective, WikiHouse stands out by incorporating principles of circular economy, resource efficiency, and material reuse, with a particular focus on wood as a renewable resource with low environmental impact. This application aligns comprehensively with long-term social, economic, and environmental sustainability, marking a significant advancement in the field of sustainable construction.

5. Conclusions

When comparing the versatility of AI-based parametric software and human skills, it can be concluded that the use of software such as Grasshopper version 1.0.0007 has significantly improved design efficiency and reduced material usage in the manufacturing of modular parts for the Wikihouse system. The Grasshopper software version 1.0.0007, combined with the open-source nature of the system, is key to addressing material scarcity, reducing energy consumption in construction, and lowering costs associated with manufacturing and processing. These tools enable faster and more efficient development and, with ongoing digitization, systems like Wikihouse are increasingly important due to their open-source nature, promoting dissemination and enhancing the viability of executing architectural projects in various locations.

In the construction system developed in this research, several advantages and disadvantages can be identified when considering its application in construction in terms of the physical environment, climatic conditions, and user comfort needs. In the case of the Wikihouse system, the use of eco-friendly materials, such as wood, stands out, offering numerous benefits. Wood not only contributes to maintaining and creating a favorable environment for both the surroundings and its users but also possesses physical properties that make it widely accessible and sustainable. Its availability and ease of use make it an efficiently sustainable option.

The execution of architectural projects involves the need to meet requirements that cover the complex and specific needs of each project. However, architecture does not necessarily follow a strictly linear approach. Based on this premise, it can be inferred that the design of an architectural space should adapt to the environment and specific needs.

Regarding the capabilities of the Wikihouse system, its virtuous ability to be implemented in various locations stands out due to its efficient assembly feature, without being limited to a rigid or strict modular structure. Therefore, this system provides flexibility in design, which is a distinctive feature of architectural works.

Author Contributions: Methodology, D.E.; Validation, V.R.; Investigation, E.P., H.V., J.F. and L.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

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

References

1. Nolazco Cama, J.L.; Cespedes Reynaga, N.; Salas Fernandez, H. Relación entre innovación y empleo en la industria manufacturera peruana, 2012–2014. *Apuntes* **2020**, *47*, 213–253. Available online: http://www.scielo.org.pe/scielo.php?script=sci_arttext&pid=S0252-18652020000200213&lng=es&nrm=iso (accessed on 15 January 2023). [CrossRef]
2. Grupo Intergubernamental de Expertos sobre el Cambio Climático. Cambio climático 2021. In *The Physical Science Bases*; Panel Intergubernamental sobre Cambio Climático: Ginebra, Switzerland, 2021.
3. Unión Europea. *La Acción Climática de la UE y el Pacto Verde Europeo: Hacer que Nuestras Casas y Edificios Sean Aptos para un Futuro Más Verde*; Unión Europea: Bruselas, Bélgica, 2021.
4. Shirinbakhsh, M.; Harvey, L.D. Edificios de energía neta cero: La influencia de la definición en las emisiones de gases de efecto invernadero. *Constr. Energ.* **2021**, *247*, 111118.
5. Taylor, C.; Roy, K.; Dani, A.A.; Lim, J.B.P.; De Silva, K.; Jones, M. Ofrecer viviendas sostenibles mediante la elección de materiales. *Sostenibilidad* **2023**, *15*, 3331.
6. Martínez-De-Alegría, I.; Río, R.-M.; Zarrabeitia, E.; Álvarez, I. La demanda de calefacción como indicador de rendimiento energético: Un estudio de caso de edificios construidos bajo el estándar de casa pasiva en España. *Política Energética* **2021**, *159*, 112604.
7. Pérez, J.M.G. The Real Estate and Economic Crisis: An Opportunity for Urban Return and Rehabilitation Policies in Spain. *Sustainability* **2010**, *2*, 1571–1601. [CrossRef]
8. Daher, A. El sector inmobiliario y las crisis económicas. *EURE* **2013**, *39*, 47–76. Available online: http://www.scielo.cl/scielo.php?script=sci_arttext&pid=S0250-71612013000300003&lng=es&nrm=iso (accessed on 15 January 2024). [CrossRef]
9. CEPAL. La Economía del Cambio Climático en América Latina y el Caribe Paradojas y Desafíos del Desarrollo Sostenible. 2015. Available online: https://repositorio.cepal.org/server/api/core/bitstreams/ca0445d3-e3f3-4f40-a5ff-057a9a34f016/content (accessed on 20 June 2023).
10. Cobo, A. El Valor Inmobiliario de la Sostenibilidad. Upm.es. 1 December 2021. Available online: https://oa.upm.es/67053/1/TFG_Ene21_Cobo_Sanchez_Alberto.pdf (accessed on 6 June 2023).
11. REVESCO. Revista de Estudios Cooperativos. ISSN 1885-8031. Available online: https://revistas.ucm.es/index.php/REVE/article/view/67334 (accessed on 16 August 2023).
12. Torres, D.; Ruiz-Tagle, J. ¿Derecho a la vivienda o la propiedad privada? De la política pública a la informalidad urbana en el Área Metropolitana de Lima (1996–2015). *EURE* **2019**, *45*, 5–29. Available online: http://www.scielo.cl/scielo.php?script=sci_arttext&pid=S0250-71612019000300005&lng=es&nrm=iso (accessed on 15 January 2024). [CrossRef]

13. Espinoza, A.; Fort, R. Planificar la informalidad: Herramientas para el desarrollo de mercados de "urbanizaciones informales planificadas". *Análisis Propues* **2018**, *40*, 2–4. Available online: https://www.grade.org.pe/wp-content/uploads/GRADEap40.pdf (accessed on 8 May 2023).
14. Zucchetti, A.; Freundt, D.; Cánepa, M.; Carranza, A. *Ciudades del Perú. Primer Reporte Nacional de Indicadores Urbanos 2018. Con un Enfoque de Sostenibilidad y Resiliencia*; Periferia-WWF: Lima, Peru, 2019. Available online: https://periferia.pe/assets/uploads/2020/06/cities-peru_compressed.pdf (accessed on 28 October 2023).
15. Ortiz, I.; Mayo, M.; Alvarez, J.; Espinoza, C.; Garaycochea, A.; Illanes, C.; Vivas, D.; Vásquez, P.; Ramos, L. Los retos de las ciudades del Perú frente al cambio climático. Aproximaciones desde la Justicia Ambiental. In *Desafíos y Perspectivas de la Situación Ambiental en el Perú: En el Marco de la Conmemoración de los 200 Años de vida Republicana*; Pontificia Universidad Católica del Perú: San Miguel, Peru, 2022; pp. 414–440.
16. Lorén, A.P. Fabricación Digital de Elementos Constructivos. Bachelor's Thesis, Universidad Politécnica de Madrid, Madrid, Spain, 2017.
17. Alfonso, B.R.B. Diseño computacional en la conceptualización arquitectónica: Conceptos principales. *Rev. Arquit. Ing.* **2021**, *1*, 1–12.
18. Salagean-Mohora, I.; Anghel, A.A.; Frigura-Iliasa, F.M. Photogrammetry as a digital tool for joining heritage documentation in architectural education and professional practice. *Buildings* **2023**, *13*, 319. Available online: https://www.mdpi.com/2075-5309/13/2/319 (accessed on 25 May 2023). [CrossRef]
19. Secchi, C.; Piaia, L.; Avila, P.; Scariot, A. Applying the Wikihouse Constructive System in Architecture Atelier: From Teaching to the Materialization of Urban Furniture. Available online: http://pdf.blucher.com.br.s3-sa-east-1.amazonaws.com/designproceedings/sigradi2020/103.pdf (accessed on 21 June 2023).
20. Sandoval, C. Arquitectura Reconfigurable y Redes Inteligentes Aplicadas al Diseño Sostenible en Smart City. Researchgate.net. 2018. Available online: https://www.researchgate.net/profile/Cecilia-E-Sandoval-Ruiz/publication/324703648_ARQUITECTURA_RECONFIGURABLE_Y_REDES_INTELIGENTES_APLICADAS_AL_DISENO_SOSTENIBLE_EN_SMART_CITY/links/5addf291458515c60f5f7ce0/ARQUITECTURA-RECONFIGURABLE-Y-REDES-INTELIGENTES-APLICADAS-AL-DISENO-SOSTENIBLE-EN-SMART-CITY.pdf (accessed on 16 July 2023).
21. Rocha, B.; Alvarenga, A.; Bolssoni, G. Open-Source Social Housing Architecture: Wikihouse "Sr. Manoel". Available online: http://papers.cumincad.org/data/works/att/sigradi2021_49.pdf (accessed on 21 June 2023).
22. Hamkhiyan, T. Diseño de un Edificio Residencial de Gran Altura Mediante Construcción Modular Eficiente MEMORIA Autor. Available online: https://upcommons.upc.edu/bitstream/handle/2117/173765/tfm-memoria-taronh.pdf (accessed on 15 June 2023).
23. Faria, I.; Martinez, A. Wikihouse: A Parametric Approach for Generating Different Spatial Arrangements. Researchgate.net. 1 February 2023. Available online: https://www.researchgate.net/profile/Andressa-Martinez/publication/366790169_Wikihouse_a_parametric_approach_for_generating_different_spatial_arrangements/links/63b26770c3c99660ebc088bf/Wikihouse-a-parametric-approach-for-generating-different-spatial-arrangements.pdf (accessed on 18 June 2023).
24. Mendonça, D.; Passaro, A.; Castro, G. WikiHouse: A Generative and Parametric Tool to Customize Curved Geometries. Researchgate.net. 2018. Available online: https://www.researchgate.net/profile/Goncalo-Henriques/publication/328681413_WikiHouse_A_Generative_and_parametric_tool_to_customize_curved_geometries/links/5bdd9450a6fdcc3a8dbb2ce8/WikiHouse-A-Generative-and-parametric-tool-to-customize-curved-geometries.pdf (accessed on 24 August 2023).
25. Nardelli, E.S.; Luiz, A.F. Wikihouse System applied to the Minha Casa Minha Vida Program. Cumincad.org. Available online: http://papers.cumincad.org/data/works/att/sigradi2016_461.pdf (accessed on 20 April 2023).
26. Open Source, Scientific Journals. El Software Libre y las Revistas Científicas. Available online: https://ojs.southfloridapublishing.com/ojs/index.php/jdev/article/download/414/387/1261 (accessed on 18 August 2023).
27. Pérez De Lama, J.; Gutiérrez, M.; García, R.; José, J.; Bordallo, O. Fabricación Digital, Código Abierto e Innovación Distribuida. Upv.es. Available online: https://riunet.upv.es/bitstream/handle/10251/15018/P%C3%89REZ%20DE%20LAMA%20J-GUTI%C3%89RREZ%20M-S%C3%81NCHEZ%20LAULH%C3%89%20J%20M-OLMO%20J%20J_Fabricaci%C3%B3n%20digital,%20c%C3%B3digo%20abierto%20e%20innovaci%C3%B3n%20distribuida.pdf?sequence=1 (accessed on 25 May 2023).
28. Priavolou, C.; Niaros, V. Assessing the Openness and Conviviality of Open Source Technology: The Case of the WikiHouse. *Sustainability* **2019**, *11*, 4746. Available online: https://www.mdpi.com/2071-1050/11/17/4746 (accessed on 25 May 2023). [CrossRef]
29. Bonvecchi, L.; Bustos, H.; López, J. "Arquitectura Modular; el Pragmatismo Como Herramienta de Diseño" [Investigación]. Universidad de Belgrano Facultad de Arquitectura y Urbanismo. Available online: http://repositorio.ub.edu.ar/handle/123456789/9454 (accessed on 20 June 2023).
30. Quimis, C.; Lisbeth, E.; Pezo, J.A.M.; Arévalo, J.J.P. Influencia de los materiales de la envolvente en el confort térmico de las viviendas. Programa Mucho Lote II, Guayaquil. *Univ. Soc.* **2019**, *11*, 303–309. Available online: http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S2218-36202019000400303&lng=es&nrm=iso (accessed on 16 May 2023).
31. Quezada, E.; Burneo, X. (s/f). Arquitectura Modular Basada en la Teoría de los Policubos Modular Architecture Based on the Theory of Polycubes. Cumincad.org. Recuperado el 18 de Enero de 2024. Available online: https://papers.cumincad.org/data/works/att/sigradi2012_84.content.pdf (accessed on 15 January 2023).
32. Hernández Falagán, D.; Ziaiebigdeli, M. Parametric Architecture beyond Form—Klein and Price: Pioneers in Computing the Quality of Life in Housing. *Architecture* **2022**, *2*, 1–17. Available online: https://www.mdpi.com/2673-8945/2/1/1 (accessed on 25 May 2023). [CrossRef]

33. Losavio de Ordáz, F.; Guillén-Drija, C. Marco conceptual para un diseño arquitectónico basado en aspectos de calidad. *Sapiens* **2006**, *7*, 119–138.
34. Quezada, E. Arquitectura Modular Basada en la Teoría de los Policubos. (Trabajo de Titulación de Arquitecto). UTPL. Available online: http://dspace.utpl.edu.ec/jspui/handle/123456789/3195 (accessed on 21 June 2023).
35. Lopera, A. Arquitectura Flexible: Open Building en Viviendas. Master's Thesis, Universidad Politécnica de Madrid, Escuela Técnica Superior de Arquitectura. Available online: https://oa.upm.es/47501/1/TFG_Jabbour_Diaz_David.pdf (accessed on 21 June 2023).
36. Cárcel, J.; Peñalvo, E.; Pascual, M.; Albiol, J. Digitalización de la Construcción. Editor. Científica 3 Cienc. 2021.
37. Cuervo, M. Tecnologías Digitales de la Construcción. Edu.co. 2020. Available online: https://repositorio.uniandes.edu.co/server/api/core/bitstreams/24d98b14-0404-4f2d-97a3-288ae0c19d42/content (accessed on 23 May 2023).
38. Aronés, M.; Mendoza, A. Guía de Labores de Control Usando Herramientas Digitalizadas para Optimizar los Tiempos del Staff de Producción en Partidas de Concreto Armado de Edificaciones Multifamiliares en Lima Metropolitana [Universidad Peruana de Ciencias Aplicadas]. 2021. Available online: https://repositorioacademico.upc.edu.pe/bitstream/handle/10757/653223/Aron%C3%A9s_VM.pdf?sequence=3 (accessed on 23 May 2023).
39. Priavolou, C. The Emergence of Open Construction Systems: A Sustainable Paradigm in the Construction Sector? 2018. Available online: https://jfsdigital.org/articles-and-essays/2018-2/the-emergence-of-open-construction-systems-a-sustainable-paradigm-in-the-construction-sector/ (accessed on 24 May 2023).
40. Romero Quidel, G.; Soto Acuña, M.J.; Rojas Herrera, C.J.; Rodríguez Neira, K.; Cárdenas-Ramírez, J.P. Assessment of Modular Construction System Made with Low Environmental Impact Construction Materials for Achieving Sustainable Housing Projects. *Sustainability* **2023**, *15*, 8386. [CrossRef]
41. Ambrósio, I.; Pena, A.C. Wikihouse: A Parametric Approach for Generating Different Spatial Arrangements. Cumincad.org. 2022. Available online: https://papers.cumincad.org/data/works/att/sigradi2022_133.pdf (accessed on 18 September 2023).
42. Martín, S. Instituto Nacional de Estadística e Informática. Gob.pe. Available online: https://www.inei.gob.pe/media/MenuRecursivo/publicaciones_digitales/Est/Lib1573/22TOMO_01.pdf (accessed on 21 June 2023).
43. El Clima en Moyobamba, el Tiempo por mes, Temperatura Promedio (Perú)—Weather Spark. Weatherspark.com. Available online: https://es.weatherspark.com/y/21433/Clima-promedio-en-Moyobamba-Per%C3%BA-durante-todo-el-a%C3%B1o (accessed on 21 June 2023).
44. Aquino, I. "Aplicaciòn de Sistemas de Ventilación Natural para el Confort Térmico en los Ambientes de una Vivienda Unifamiliar Distrito La Merced" (Trabajo de titulación de Arquitecto). Universidad Continental. Available online: https://repositorio.continental.edu.pe/bitstream/20.500.12394/4990/2/IV_FIN_106_TE_Aquino_Aquino_2018.pdf (accessed on 21 June 2023).
45. Escamilla, J.I.G. Arquitectura Modular. Una Aproximación a la Utilización y Elementos de este Tipo de Arquitectura en la Actualidad. Available online: https://www.academia.edu/34213254/Arquitectura_Modular_Una_aproximaci%C3%B3n_a_la_utilizaci%C3%B3n_y_elementos_de_este_tipo_de_arquitectura_en_la_actualidad?email_work_card=view-paper (accessed on 23 June 2023).
46. Climent, A. Economía circular aplicada a la arquitectura espejismo o realidad. *Limaq* **2021**, *007*, 29–71. Available online: https://dialnet.unirioja.es/servlet/articulo?codigo=8460579 (accessed on 22 June 2023). [CrossRef]
47. Madronero, S.; Guzman, T. Desarrollo sostenible. Aplicabilidad y sus tendencias. *Tecnol. Marcha* **2018**, *31*, 122–130.
48. Husgafvel, R.; Sakaguchi, D. Circular Economy Development in the Wood Construction Sector in Finland. *Sustainability* **2023**, *15*, 7871. Available online: https://www.mdpi.com/2071-1050/15/10/7871 (accessed on 18 October 2023). [CrossRef]
49. Dsilva, J.; Zarmukhambetova, S.; Locke, J. Assessment of building materials in the construction sector: A case study using life cycle assessment approach to achieve the circular economy. *Heliyon* **2023**, *9*, e20404. [CrossRef]
50. Shams, S.; Mahmud, K.; Al-Amin, M. A Comparative Analysis of Building Materials for Sustainable Construction with Emphasis on CO_2 Reduction. 21 February 2015. Available online: https://www.inderscience.com/info/inarticle.php?artid=47767 (accessed on 25 November 2023).
51. Carbon Storage in Harvested Wood Products (HWP). (s/f). Unece.org. Recuperado el 18 de Enero de 2024. Available online: https://unece.org/forests/carbon-storage-harvested-wood-products-hwp (accessed on 17 January 2024).
52. Atapuma Naranjo, M.F.; Jarrín Vivar, C.H.; Mora Martínez, C.J. Estudio Técnico Económico Comparativo Entre Proyectos Estructurales de Hormigón Armado, Acero y Madera para Viviendas y Edificios. 2013. Available online: http://www.dspace.uce.edu.ec/handle/25000/740 (accessed on 22 June 2023).
53. Kostakis, V.; Niaros, V.; Dafermos, G.; Bauwens, M. Design global, manufacture local: Exploring the contours of an emerging productive model. *Futures* **2015**, *73*, 126–135. [CrossRef]
54. Kostakis, V. How to Reap the Benefits of the "Digital Revolution"? Modularity and the Commons. *Halduskultuur Est. J. Adm. Cult. Digit. Gov.* **2019**, *20*, 4–19. [CrossRef]
55. Pantazis, A.; Meyer, M. Tools from below: Making agricultural machines convivial. *Greek Rev. Soc. Res.* **2020**, *155*, 39–58. [CrossRef]