Design and Robot Assisted Carpentry Joints for wooden houses

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Abstract

In Chile, the participation and presence of women in research in the fields of construction and architecture has increased considerably in recent years, but there is still a long way to go. The experimental research presented in this article not only demonstrates female leadership in the area of mechanization and development of robotic processes for the area of architectural design and construction, but also proposes a structural and prefabricated innovation to optimize the processes of assembly and production of houses in Chile.

This study addressed the design of a traditional wooden structure of posts and beams for a single-family house in glued laminated wood of Douglas fir, a native specie grown in Southern Chile, based on robotized carpentry joints. The final objective was to design, analyze and build a prefabricated structural system with carpentry joints for the optimization of the construction and assembly process, through robotic mechanization and on-site assembly. The research was the final project of a female student to graduate with the professional degree of architect. Then, the development of the design process to build was also carried out by a team led by a female professor with three females last-year of architecture students.

Keywords

Women in research, Wood Engineering, Robot assisted Carpentry.

1 Introduction

At the present time the development and involvement of women in areas of science and technology in Chile has become a relevant issue, and despite it is growing, we are still considerably in deficit compared to male development. This is revealed when carrying out an analysis of the National Fund for Scientific and Technological Research (FONDECYT), *created as an instrument to promote scientific and technological development in Chile, fosters the initiative of individuals and research groups by funding scientific and technological research projects in all fields of knowledge* (CONICYT, 2017). The study depicted that grants led by women had an upward trend - moderate from 24.2% in 2009 to 32% in 2014. However, despite these advances, significant gaps remain in the participation of women in the training and promotion of scientific careers, among which are: 1. Horizontal inequality: a low participation of women in the academic disciplines of science, technology, engineering and mathematics. (STEM). 2. Vertical inequality: the decrease in the participation of women as the research career progresses, and its consequent, less presence in positions of greater scientific leadership (CONICYT, 2017). Likewise, with respect to women dedicated to STEM professions, the percentage of women in Chile is far below at the international level. Only 34% of women are academically dedicated to STEM careers (CONICYT, 2017) compared to 46%, for example, of women in STEM professions in the United States (EEUU, 2015). In both cases showing the lowest of the percentages in the engineering area. It is necessary to innovate in the different areas of science to attract the female presence to research, development and innovation. The project seeks to

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contribute on robotic design and mechanization transferred from advances developed worldwide to the Chilean reality, highlighting the female intervention through the whole process.

At the same time, the applications of robotics in architecture and design have advanced much leading to a great variety and possibilities for utilization (Architecture, 2016). However, robotic carpentry is still at a beginning point, even more so when we talk about the use of robots for the machining of carpentry joints.

The main objective of this study is the use of robotically mechanized carpentry joints carved on laminated posts and beams timber as the structural component for housing construction. The mechanization is to promote prefabrication and structure accuracy for the development of housing, based on the native property of the material, as well as securing sustainability within the process .

2 A Wood Country

In Chile, laminated wood and mechanization processes are very recently incorporated into the building construction domain, both in the areas of structural research and timber design for industrialized production. Although there have been incentives to involve robotics in the area of architecture and design, and incentives for participation of female as well, there is very few experimental samples nationwise and it is still an expensive I+D+i area. And, when reviewing the few cases, most of them have been developed by males, being even less presence of female participation in this field than the general third dedicated to STEM/STEAM sector within the country (CONICYT, 2017).

Chile is one of the countries with the largest timber production of the world, and the wood industry is one of the most relevant activities at the national level, contributing with the 3% of GDP, (Lop, 2021). In recent years, the construction of housing with wood has been increasing considerably, this referring mainly to sawn timber as a structuring or load-bearing element of walls and roofs. The total area built in 2018 showed an increase of 9.1%, reaching a total of 19.21 million square meter's built. Likewise, in the area of housing construction, it reached 12.35 million square meters authorized for construction, increasing by 14.8% compared to 2017, with 14.4% of this amount (1.77 million m2) using wood as the main element in walls (Forestal, 2020). One of the strategic focuses of this research has been to undertake actions aimed at promoting massive wood construction, following the path of most of forest indutry countries as well as other countries that have discovered in this type of construction, opportunities for environmental, social and economic improvements.

2.1 Sustainability of wood construction

Although, Chile is a wood producing country, the highest percentage of housing constructions currently corresponds to reinforced concrete structures considering 55.9% of the total of new building permission authorized in the last year, compared to new building permission where wood as the main building material was specified only covers 12.7% (Forestal, 2020). The concrete industry is the biggest challenge to overcome nationwise, as it is characterized by being a time-consuming industry, energy, CO_2 emissions and dependence on water, which also influences the final cost. However, it is widely proven technology in terms of earthquake resistance for a highly sesimic country, fully comparable to wood construction, however concrete and masonry are culturally most accepted and preferred by people in many places (Hoibo et al, 2015).

Thus, the structural system proposed in this research is designed to be prefabricated and modular, reducing the carbon footprint in the use of machinery, less pollution when prefabricating and less in-situ pollution at the time of construction (assembly). If we add to this structural system the factor of using robotized carpentry in its joints, CO_2 emissions decrease even more, since the manufacture of steel parts produces more pollution than the design of the timber joints. On the other hand, it increases the total cost of the structure to 40% of the final value (M.R.Cerda, 2020). Finally, the use of domestic laminated and manufactured wood and from a sustainable forest management, provides the project with low CO_2 emission factors, deriving on a completely sustainable life cycle.

2.2 Laminated Wood

The most widely used wood product at the national level is sawn timber, which functions as a load-bearing material as a whole and not in itself, which is why it cannot compete structurally with reinforced concrete. However, since approximately the year 2000, the country has been innovating with laminated wood, both domestically produced and imported (Mercurio, 2003). Although the constructions with laminated or massive wood products in the world have had a greater development and progress since much earlier, in Chile there is still a lot to be known and applied (González, 2020). Also the normative development that is necessary to compete structurally with concrete, which is currently in process.

The national production of sawn timber is 8,034,400 cubic meter per year, mostly of radiata pine and without considering the production of laminated wood, which is not currently industrially marketed. Only approximately 10 lumber companies are engaged in the manufacture of glulam or solid wood products in the country, being mostly glulam with defined and commercial dimensions, while for customized designs the proposals decrease considerably (Madera, 2021). The glulam used for this project was made of domestic Douglas fir, produced and machined in Villarrica and then transported to Valparaíso for construction.

2.3 Structural system definition

The project corresponds to a two-story prototype house of 72,85 square meter, which was a chosen unit of 5-storey building adapted for a single family house, it is founded on isolated reinforced concrete footings with customized steel connectors in its 8 columns. The structural design is defined as a mixed construction system which is composed of a primary post and beam structure and a secondary structure with a diaphragm of sawn timber trusses. The primary structure is made of certified Douglas fir laminated timber, provided by the national sawmill Voipir, Villarrica. This structure is defined as a heavy post and beam type framing, with dimensions of 185x185mm for transverse beams and 185x360mm for longitudinal beams and columns. The total amount of glulam used is 11.85 cubic meter. This structure is joined by means of robotized reinforcement carpentry joints in its longitudinal axes and hidden steel connectors in its transverse axes. Both are mechanized through robotic processes.

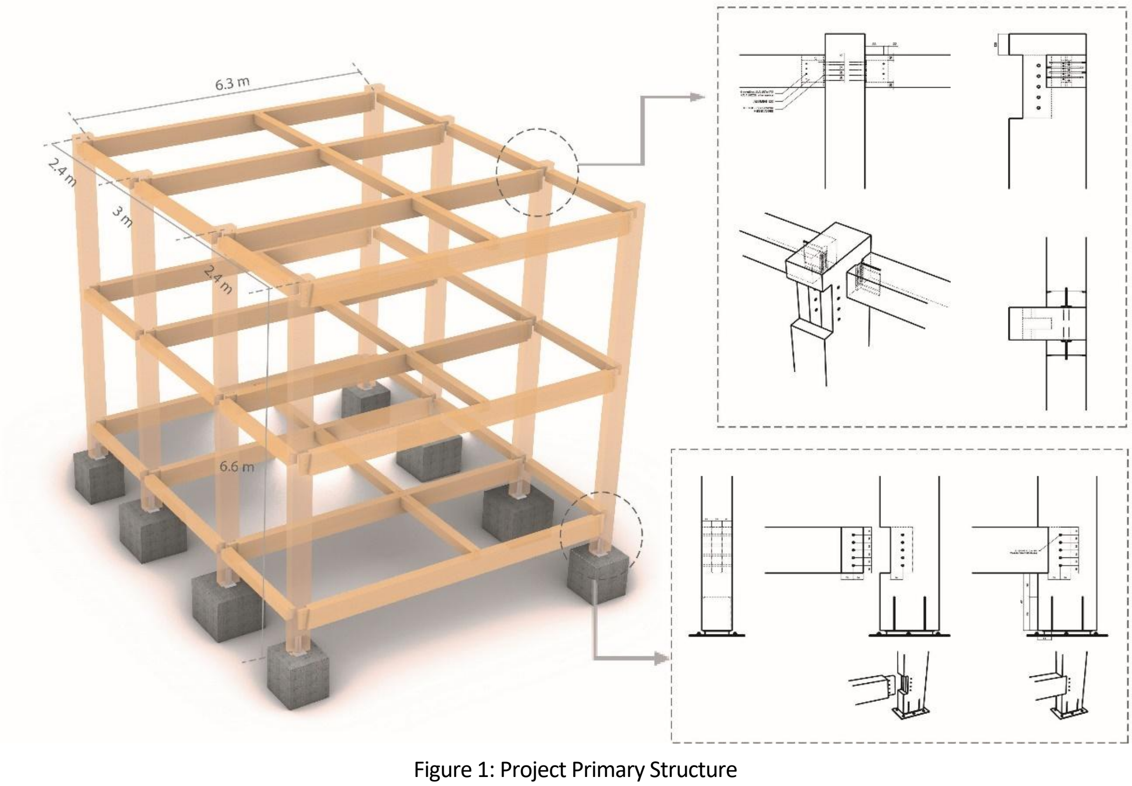


Figure 1: Project Primary Structure

Large sections are required for a heavy framing system of post and beam construction type, and even more so in the case of reinforcing carpentry joints or carpenter's joinery. This is due to the fact that when manufacturing a carpentry joint, a section of the wood element is cut out, so that by using large sections it does not lose its structural capacity. In addition, it has been established that the connections of the post and beam construction system are usually elastic structures in order to resist forces and damage caused by earthquakes. Secondly, according to the precedents studied in Valparaíso, timber framing systems, thanks to the freedom of design, make it possible to adapt the buildings, mainly orthogonal, to any site. The freedom of design is also established in the freedom of interior diaphragm modifications, determining in several cases studied, that the trusses are the main responsible for managing the global forces (horizontal and vertical), in such a way as to provide the necessary rigidity only with the primary structure. On the other hand, it is determined that the most efficient way to build the secondary structure is independently from the primary one, since, by supporting the secondary structure on the primary one, it produces a decreasing effect of the general structuring, adding extra weight and producing failures later on (M.R.Cerda, 2020).

3 Robots in Architecture

The biggest challenge of the application of robotic work in architecture is the relationship between the use of digital software and the physical application on the material, because the most efficient way of movement of the robotic arm and the optimal way of a linear flow between programs must be sought (Johannes Braumann, 2012). The objective is to be able to define customized movement paths for different cuts or processes in the material, so that a more industrialized and accurate process can be designed when replicating in blocks. For this purpose, computational add-ons have been developed, such as the one used in this research KuKA | prc, which are integrated into the software used for architectural design (Rhinoceros and Grasshopper) providing the possibility of planning and simulating the movement of the robot within the CAD environment, also generating robot control data files that can be executed directly (Johannes Braumann, 2012).

The ultimate goal of these add-ons is to favor the personalized development of robot movements by creating new design strategies, providing the further advantage of creating direct feedback when making changes to the initial geometry, allowing a more intuitive relationship of the action-reaction relationship. This directly favors the objectives of this research, since it allows to automate the generation of robot control data for mass customization of elements.

Among the major female influences in the progress of robotics in architecture is Sigrid Brell-Cokcan, who has not only investigated the development of software in the computational design process, but has also developed constructive processes with them. Some of the research and applications provided by the robotic arm have been mainly the use of grippers, milling and welding equipment, as well as progress in 3D printing. However, woodworking has also had many technological advances, one of the examples is the project carried out by TUVienna where they created a canopy structure of more than 5 by 5 meters and a diagonal of 7 meters (Baris Cokcan, 2014). While it is not a building project per se and does not have any structural function, it is important to understand how the various applications were done.

The robot used to perform the design is a KUKA KR16 with a built-in milling spindle. However, one of the biggest problems was the work space needed by the robotic arm to perform the different cutting trajectories. In addition, there is a relevant factor when using a material such as wood, because although it is very versatile naturally to create different shapes (bending or cutting) it is also an anisotropic non-homogeneous material, so the accuracy of the machining process can be affected (Baris Cokcan, 2014).

Thus, this research aims to be a contribution to the current developments intervening in the laminated wood structures through machining process and joint designs, so that the robotic arm not only works as a fastener or linear milling machine, but also develops the use of its 6 axes with a structural objective and direct contribution to the development of predefined elements such as steel connectors.

3.1 Robotized Carpentry (RC)

Robotized Carpentry offers a value proposition based on the prefabrication of assembled wood framing by means of carpentry joints of complex geometry. In this way, the industrialized production of wooden houses with carpentry joints made by robots will allow us to take advantage of the Chilean wood industry, reduce costs in metallic joints and take advantage of the development by reducing construction times. In Chile there are currently approximately 500 industrial robots installed, which serve in different areas of the industry, without considering a significant application in the Chilean construction area, and only one in the laminated wood industry (M.R.Cerda, 2020). For this reason, it is intended to shorten this technological gap, through a constructive proposal using RC methods and systems.

Considering the above, it is proposed the design of robotized framing carpentry joints as a technical solution of the mixed structural system of Post and Beam, in which 3 critical design points are considered; 6.30 m long longitudinal pillar-beam joint, 2.4 and 3 m transverse pillar-beam joint and the pillar-foundation joint. On the other hand, wood has a very particular characteristic of fire resistance, in such a way that it is able to carbonize completely before reaching the core in a longer period of time. This is what, as a material, makes it more efficient structurally at the moment of a fire. Thus, the RC design is chosen for the post and beam joints of the large frames, favoring the primary structure for both fire and seismic movements. In addition, hidden connectors are established in the cross sections and in the foundations, in such a way that they continue with the logic proposed for the RC system, providing a longer collapse time for the structure.

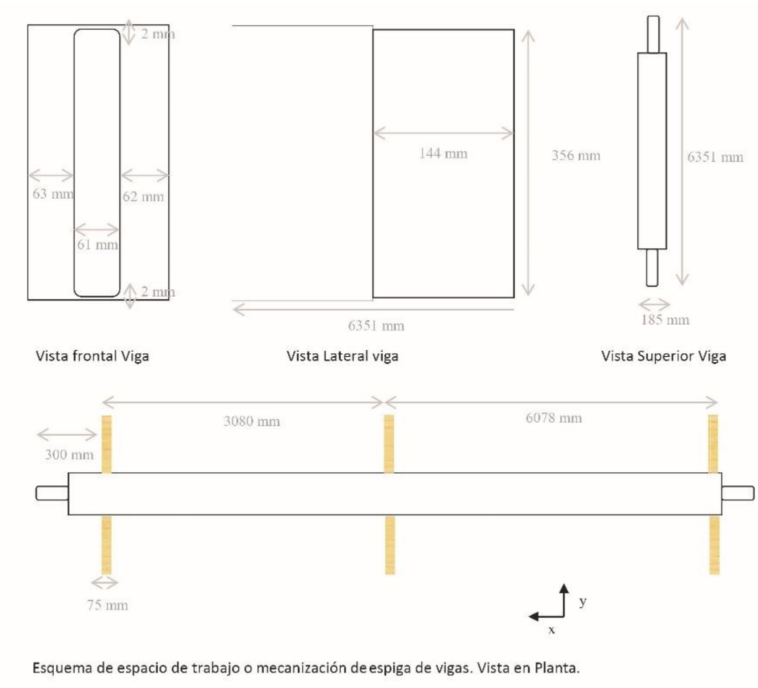


Figure 2: Bean’s mechanized scheme

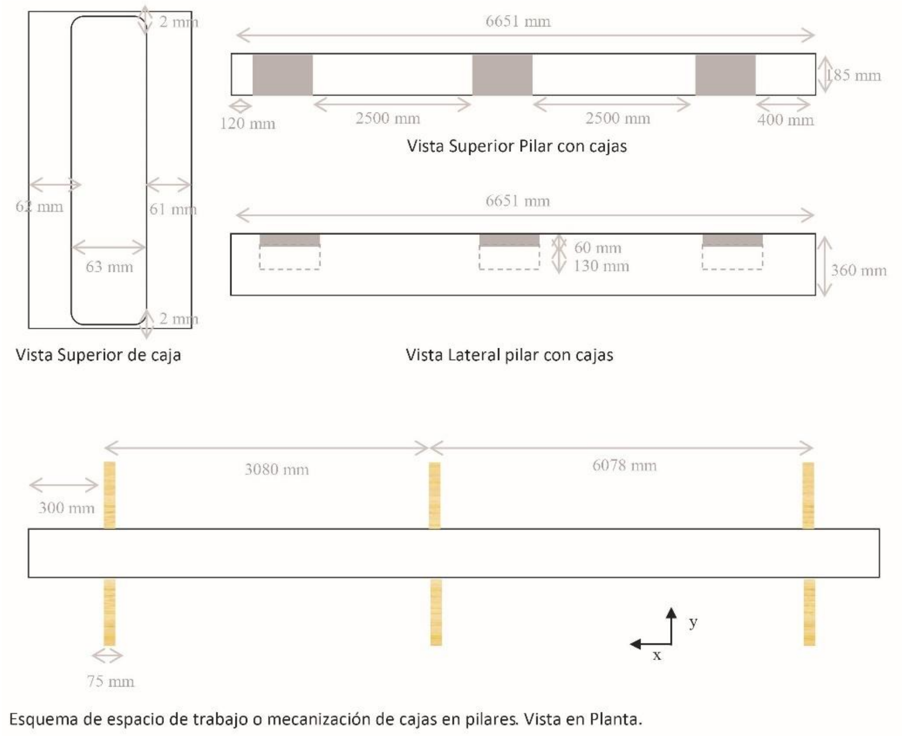


Figure 3: Box's mechanized scheme

To define the final design of the assembly to be carried out, a civil engineer was consulted prior to the machining process, thus corroborating the most efficient design of the structural frame (2 columns and 3 beams of 6.30 m in length). The final design corresponds to a carpentry joint of rectangular box and dowel joined by steel dowels with a circular base.

For the machining process, a prefabrication of 24 dowels in 12 beams of 185x360 mm section and 6300 mm long is determined. And 24 boxes in 8 columns of 185x360 mm section and 6600 mm long. These assemblies make up the number of 4 transverse frames of the primary structure of the project. The box has a total depth of 190 mm, of which 60 mm are waiting, and the dowel is 130 mm long, this in order to achieve a greater separation of the pins with the shoulder. The machining process was carried out in the warehouse of Voipir sawmill, the timber provider for the project as well.

Figure 4: Box and dowel mechanization, Voipir, Villarrica, 2020

The machining of the project structure considers:

- Average manpower of 2 people and a KUKA robotic arm.
- Estimated weight of complete structure 5600 kg
- 9 days of machining with 8 hours per day for the 4 frames with CAR
- 72 repetitions of machining process for making 1 dowel giving a total of 144 mm dowel length.
- 32 repetitions of machining process for making 1 shoulder without box giving a total of 64 mm.

- Total Pre-Machining Time = 443 hr
- Programming Time= 13.8 hrs
- Machining Process Time for Dowels = 33.7 hrs
- Machining Process Time for Boxes= 32.2 hrs
- TOTAL PROCESS TIME= 522.7 hrs
- TOTAL WORKING DAYS TIME= 65.3 days of 8 hours x day

On the other hand, added to the total machining labor time is the cutting of the beams that receive the Rothoblass ALUMINI125 concealed steel connector. This prefabricated connector has normally been previously installed on site, having a low installation accuracy, so it was decided to provide an advantage with the machining.

For this machining, Autocad (2D drawing), Rhinoceros (3D), Grasshopper (3D model transfer to movement programming) and the GH KUKA|prc plugin for trajectory simulation and direct transfer to the robotic arm were used. One of the most relevant tools in architectural design is Grasshopper, since algorithms are created through visual programming, connecting the output of a component with the input of another component that translates into an acyclic and directed graph, which finally translates into the movements expected by the industrial robot. As Grasshopper treats each component separately, even invalid solutions are displayed. This process allows for a much smoother workflow, compared to programming languages where only the wrong line is displayed in the debugger (Johannes Braumann, Real-Time Robot Simulation and Control for Architectural Design, 2012).

In addition, as an annex tool, the bridge crane from Voipir was used, with which the wooden parts were transported to be machined and/or to change parts of the working sector (both actions were not considered in the machining working time). This bridge crane considers the total width of the Voipir shed, which is 28 m and supports a total load of 3.2 tons.

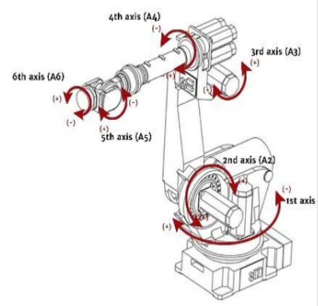
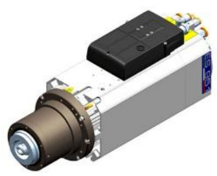
Robotic Arm KUKA KR2240_2:	Straight Milling Internal Cutter	Gripper Cone iso30 – ER32	Electrical-Spindle ES_951:
6 axles of freedom	20/19 mm diameter	50 mm diameter	With automatic clamping system
240 kg load support	250 mm total length	2-20 mm capacity	Asynchronous Motor
Robot modified and assembled from parts	200 mm usable length	1 mm tightening range	Rotation Speed Mxx.: 24.000 rpm Min.: 8.000 rpm
Rail support F.EE GmbH		60 mm length	
			

Table 1: Tools and machine features applied in the mechanization process.

3.2 Project Construction

After being mechanized in Villarrica (Southern Chile), the laminated wood was transported to Valparaíso to begin construction of the house. Upon receiving the wood in the construction sector, the dimensions of all the elements were verified, since under ambient temperature it could have had natural modifications; however, since the laminated wood was of large dimensions, the changes in the elements were minor, considering a range of ±2mm of expansion of the material.

The project was located on the Rocuant hill in Valparaiso, destined to be a house for a family that lost their original home in the fire of 2019. Originally the project was to be located on a flat site, so the considerations of lifting and assembly of the structure should not have had a greater complexity, however, the complications in the field tested the versatility of adapting the structure to sloping terrain.

To assemble the 4 structural frames, 9 construction workers were required, since each frame had a total weight of 1 ton, making the transfer and movement of each of the pieces quite complex. These frames consider 2 pillars and 3 longitudinal beams of 6.3m in length. The whole procedure was carried out manually, with the help of a cordless drill to insert the corresponding dowels in each joint. The precision of the joints was quite accurate, unlike a box and dowel joint where 2 cm had to be adjusted to achieve a perfect fit. The assembly of the 4 structural frames was carried out horizontally to the ground to be later hoisted and installed on their foundation connectors.

The most complex process of the assembly work was the hoisting of the 4 structural frames by means of a crane, for which 2 unsuccessful attempts were made and the third attempt was successful. This operation is quite complex since the site is located at the intersection of two streets, where the main access is on a steep slope. Therefore, several factors had to be taken into consideration to carry out the maneuver. Each frame of the structure has a weight of approximately 1 ton, where the crane consulted had to have a capacity at its most unfavorable point greater than 1 ton.

Figure 5: Lifting of the first structural frame.

For the metal foundation joints, two 6 mm cuts were required in each column of the 4 existing frames. It was essential to make the cut as accurate as possible because if it was more than 8 mm thick it could collapse at the time of assembling the complete structure.

Figure 6: Frame instalation, column metal connectors with concrete foundation.

Finally, beams that already had previously machined metal connectors installed were mounted on top of the foundation, providing rigidity to the frame structure. They were installed manually in two days (one at each end) with the use of scaffolding, since they had to be installed from top to bottom inserting each part of the connector.

Figure 7: Complete lifting of the foor frames of the main structure.

The complete assembly process lasted 18 hours, for the primary structure lifting and installation took 10 hours resulting in a total of 28 hours of continuous work spreaded in three working days with 9 construction workers on site and one loading crane.

4 Conclusion

One of the main objectives of the project was to empirically establish the advantages of pre-fabricated production and construction with high precision robotic processes. This will enable more efficient, cost-effective and environmentally friendly design and construction processes.

For this purpose, 4 fundamental areas of development were determined in the process:

1. Organization or previous processes: a sequence of machining preparation processes had to be carried out, considering logistic processes specific to the inputs or tools to be used and/or economic factors for the development of all items. It was planned for one month, which was extended due to different factors of each supplier and design processes, due to the reduce places with the needed technologies in the country.

2. Programming: In principle it referred to the design process for the machining of the parts, which was previously prepared, however, upon arrival at Voipir there were programming problems with the robot, which when calibrated showed an error of 1.8 mm which is too much for the machining process. Thus, the programming process was extended to 2 extra days, to solve the problem of origin of the robotic arm (programming operation) and then test the machining program, previously tested in Grasshopper.

3. Machining: Manufacturing of joints with the robotic arm. This process originally involved the programming for the manufacturing of the dowels and boxes, however, due to the programming problems, the dowels became manufactured and the boxes were left pending for a later process, adding extra time and costs. This problem allowed comparing the advantages of the complete process of the building made with wood and robotic manufacturing processes with the same building in other materials and in-situ construction processes. This was one of the most relevant results at the moment of the assembly of the structure, since it visibly confirms the need for a subsequent review during and after each machining to corroborate that the process was optimal and accurate. Since the machining process was not completely supervised, it produced important differences in the dimensions of the boxes and dowels, having to make in-situ modifications in the construction.

4. Construction: One of the major factors that influenced the construction of the project was the Covid 19 pandemic, since it was previously intended to be built in 2020 with an established plan and costs, however, the forced delay of the construction due to logistical problems founds on the site and adjecencies to operate, caused the materials and processes such as transportation of material and the crane functioning to have a higher value than budgeted. Affecting the material's especifications to be changed, due to the scarcity in the market, augmenting the cost and the planned construction schedule.

Based on the information gathered and the empirical experience of the whole process, it is determined that the proposed construction system typology, prefabricated and modular, is optimal for adaptation to any site condition, however, due to its large dimensions and total weight, it is much more favorable for wide and flat site, allowing the crane to maneuver. This is mainly due to the fact that, when constructing a building taller than one level of height in a modular way, the greatest difficulties are the dimensions of the components, where the tools and machinery necessary for the process such as loading cranes need to be carfully dimensioned. This, in turn, requires more manpower for movements and larger work spaces for proper handling. On the other hand, the times and efficiency of robotic manufacturing processes depend on programming factors as well as on the elements or tools used, which can further shorten the process times. Considering the internal programming of the robotic arm, as well as in the conditions of the work space and the efficiency of the programming proposed for a correct handling of external users.

Finally, it is obtained that the project design is comparable with other materials and construction processes, being more efficient and accurate at the time of construction, however, there are still economic gaps that are not currently favorable, but that can be improved over time.

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