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COMPARATIVE RESEARCH OF SINGLE-FAMILY HOUSING CONSTRUCTION SYSTEMS BY CONSTRUCTION COST USING STRUCTURAL WOOD AND OTHER MATERIALITY

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ABSTRACT:

The wood construction massification in Chile has been considered in the last years as a strategic axis in forestry, and environmental policies, considering that this is a forestry country, the remarkable environmental contribution potential the use of this material has, and the necessity of reducing the housing deficit.

In order to evaluate the development feasibility of a massive housing wood construction, with higher quality standards than the ones traditionally used, a comparative analysis is conducted in terms of construction costs based on 4 constructive systems: wood framing, post and beam construction system, galvanized steel, and confined masonry.

The wood frame system is presented as the most competitive mainly due the wall, and roofing final cost, but also in the carcass work final cost; it is also more competitive in the construction final cost, but here the gasps are reduced. All evaluated systems have budgets that may be eligible for state subsidies.

Among the keys to improve competitivity in wood construction is the diversification of lengths, and dimensions in structural products supply. In relation to the post and beam system, traditionally associated to higher value, and size, it is concluded that is possible to develop delimited footage projects, with low cost, which also allows a greater use of the system advantages in terms of the possibility to modify the house internal distribution.

KEYWORDS: wood construction; construction system costs; lumber dimensions.

1 INTRODUCTION

In Chile, the authorized area of new housing constructions that used wood as a predominant structural material reached only 12.9% of the authorized housing area at national level in 2019 [1]. This participation of wood is in contrast with others wood-producing countries, where the participation of this material exceeds 80%, as in case of United States, Canada, Finland, and others [2].

The wood participation in the Metropolitan region housing construction, which is where the present research is focused on, reached in 2019 only 1.3% of the authorized area in the housing building permits [1].

In recent market researches carried out by INFOR [3], several construction materials demanding actors recognize the value of wood in terms of thermic, and acoustic insulation, seismic performance, and construction, and products costs. But they also claim a low valuation in durability, fire resistance, structural features, and clients' perception.

To promote wood housing construction, especially in those regions far from forest resources, a lack of wood construction culture, and where this kind of houses are perceived as a low-cost option, but with poor quality, it is necessary to promote proper construction systems, based on structural graded timber products. On the other hand, it is necessary to clear up doubts in terms of feasibility of the use of quality structural timber, with accessible construction costs for mass population, which in great proportion make use of state subsidies.

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Currently, an important opportunity is being presented to promote wood construction massively in Chile, since the Ministry of Housing, and Town Planning has applied a Housing Emergency Plan, which aims to resolve during the 2022-2025 period, at least 40% of the current housing deficit, calculated in 643.000 dwellings. This means that the goal of this period is 260.000 dwellings, from which 135.590 corresponds to new works, and 124.410 are under construction [4]. In this plan, is expected that wood starts to play a fundamental roll as a structural material. Due to the short deadlines established, it is suggested that a great part of this wood housing demand to be develop through industrialized construction. However, companies that work with these systems are recently created, and with limited capacity, so the challenge should be approached by working together with traditional construction onsite, and industrialized construction. The present research focus on the background related to the former type of construction, with the aim to incorporate in this process the small, and medium size construction companies, as well as the small, and medium size sawmill industry.

This research is approached with the purpose of evaluate costs structures, feasibility in choosing massive construction alternatives in accordance with Chile being a forestry country, and with the challenges the climate crisis brings.

The analysis is based on recent research carried out by the Area of Information, and Forest Economics' professionals, in coordination with an architecture company with a vast experience in volume calculation, and in average value, single-family housing construction projects, using different materials [5].

2 MATERIALS AND METHODS

The construction costs of four construction systems are evaluated, these systems use different predominant structural materials: wood frame (in two models, with different dimensions), wooden post-beam, steel frame, and confined masonry. These construction systems are defined hereunder.

a) Wood frame system: a frame is a constructive disposition based on the use of linear structural members, combined in different positions to build structural elements [6].

A partition is a vertical frame constituted by two posts located at short distances (between 0.30, and 1.0m) jointed by their edges with horizontal, or inclined members.

The most frequently used framing systems, since they are more cost effective, are characterized by the supporting function of the majority of their partitions that jointed together constitute the whole system, these are simple systems with butt, and nailed joints.

In the present research, two models of this construction system have been considered: framing with 2x4 members, and 2x6 members framing.

b) Post-beam system: it is constituted by horizontal, vertical, and inclined members connected one to another. They transmit the static, and dynamic loads from beams to posts (pillars), and then to foundations. It is characterized by using big dimensional, and/or laminated timber, allowing greater distances between posts.

The constant technologic development in construction materials has allow this construction system to be highlighted by its architectural features, in accordance with the modern architecture concepts. However, it is important to note that this type of solutions is not applicable in dwellings with state subsidy, basically because of its high cost. [7].

c) Steel frame: this construction system follows the same concept as the frame system aforementioned, since for its execution, linear structural members are needed, which are combined in different positions to build structural elements.

This construction system consists in light steel profiles that provide horizontal, and vertical structural solutions, partition walls, and roofing structures.

d) Confined masonry system: This construction system is constituted by reinforced concrete elements, posts, beams, and chains which completely frame brick walls. This may be executed with handmade bricks or industrialized bricks, and different materials like a clay, or aerate concrete blocks, among others. Mortar is used in brick laying.

In the first methodological phase, a general architectural model is defined upon which this research is based on, allowing a cost comparative analysis for all of the construction systems to be developed. The architectural model considers a construction area of 80 m², which represents the average declared values in building permits in 2019 [8]

The base model presents the following architectural planning:

- Living-dining. Useful area: 27 m^2
- Kitchen. Useful area: 8.06 m^2
- Room 1. Useful area: 11.53 m^2
- Room 2. Useful area: 9.05 m^2
- Room 3. Useful area: 8.25 m^2
- Bathroom. Useful area: 4.34 m^2
- Hallway. Useful area: 3.42 m^2

It should be noted that the indicated useful areas, which in total amounts to 71.65 m², are referential, since dimensions can change depending on walls thickness in each construction system.

As a part of the model's design definition, it was decided to consider a spread footing, and concrete ground in all cases. While it is true that the majority of the evaluated systems in this research can be executed with isolated footing, and flooring frame, it is also true that the foundation system, and the selected concrete base represents the country's predominant preference, basically due to cultural reasons [8]. This decision can go in detriment of systems that do not require them, but the finishing standards make this definition advisable.

As dwelling location, the commune of Santiago, in the Metropolitan region, has been considered. This region is by far the main housing demand center in Chile, representing 43% of the authorized dwellings in 2019, and 45% of the new works area. However, it has a low wood construction participation at national level, representing only 3.6% of number of dwellings, and 4.6% of the authorized housing area that uses wood as a predominant structural material in walls [9]

In a second phase, and counting on the base design, a particular structural, and architectural design was developed for each alternative, considering the features of each construction system, and trying at the same that they all share, where possible, the same useful footage, window dimensioning, and finishing materials. The suggested designs are in compliance with standards required by *La Ordenanza General de Urbanismo y Construcción* (OGUC) in relation to inhabitability, and safety.[10]

In the volume calculation process, the amounts of projected materials for each model in the corresponding unit of measure are quantified. The budgetary process continues with the development of a Unit Price Analysis (APU) for each model, where each item is identified and quantified, considering for that purpose the market value prices, and recognized suppliers in the construction industry. The APU analyses incorporate all the variables included in the execution of every item, like cost of materials put in work, workforce costs, and performance, tools, equipment, operational costs, and contractor's utilities. With APUs results, budget itemized tables were created for each model, whose final sum determines the construction direct cost, which includes general expenses, utilities, and taxes.

3 RESULTS

3.1 TECHNICAL SPECIFICATIONS OF SUGGESTED MODELS

According to the research objectives, the differences in design of the five construction models suggested are concentrated in carcass stage, and in particular, in the structure of exterior, and interior walls. To identify the cost gaps among structural materiality, foundation proposals, quality roofing, and finishings, and equivalent designs were formulated.

a) Carcass specifications

Vertical structures of walls, and partitions proposals

In case of the wood framing models suggested, vertical partition is assembled out of 2x4" sized impregnated pine posts (IPV) for the first model, and 2x6" with C16 structural grading (according to European norm) or similar for the second model. The distance between 2x4" posts is 40 cm, and 60 cm in case of 2x6", in both cases dimensions are the same for inferior, superior, and stick framing sills, and bridging. The members are dried to a moister content of 15%. The members length are 3.2 meters for 2.4" dimensions, and 4.8 meters in case of 2x6".

In the wooden post- beam model, structural posts should be laminated of 115x115 mm in members of 2.7 meters long. The anchoring will be executed with dawer inserts in stem wall, and lateral metallic connectors. It contemplates the use of structural double tee pine beams of 2x6" with C16 structural grading or similar, dried in chambers to a moisture content of 15%. Structural, and non-structural vertical partitioning uses pine IPV 2x4". The anchoring in the concrete ground is executed with expansion bolts, and posts, and beams with drywall screws.

The design suggested to the steel framing profiles model considers the use of vertical partition (perimeter, and structural) conformed by structural studs of 90x38x12x0.85 mm type. In case of inferior, and superior sills, a channel profile of 92x30x0.85 mm is used. Capping beams are considered for partitioning bearing the load from roofing, which are conformed by two studs, and a channel profile of the same type aforementioned. All the structural, and/or perimeter partitioning should be coated in the outer side with OSB panels of 11.1 mm thick.

The model suggested for confined masonry considers the use of reinforced-concrete pillars. The ironwork has 4 ribbed steel bars of 9.2, or 10 mm long, with 4 ribs every 20 cm. It will be used reinforce concrete bridging and beams with the same dimension as stem wall, as well as its ironwork. The partitioning walls will used pine framework IPV of 2x4" in all its elements.

Foundation proposals

For all framing models, a reinforced-concrete spread footing system is proposed in their perimeter axis. The stem walls correspond to reinforced-concrete chains of 15x30 cm. The stick framing beams considers the same dimension, and ironwork.

In case of confined masonry, a reinforced-concrete spread footing foundation is proposed in its perimetral axis, as well as in interior structural axis. This aspect is presented as a significant difference with the aforementioned models. The vertical structure load suggests foundations to transmit the load to the floor in all of its extent. Stem walls corresponds to the same stem wall proposed in the previous reinforced-concrete pillars of 15x30 cm.

For all proposed models, it is considered for concrete ground sub-bases the use of aggregates in different sizes compacted in layers. In the different models, it is proposed

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the construction of a reinforced-concrete ground of 9 cm thick.

Roofing structures proposals

For the three models based on wood as a structural material, as well as to confined masonry model, it has been considered a roofing structure formed by 1x4", and 2x4" IPV sized pine trusses. Above them, dry pine rafters of 1x4". It is proposed the use of a base cover in OSB of 11.1 mm, and a steel roofing sheet of the product called "PV6 zincalum"

The model based on galvanized steel profile structures presents a roofing structure conformed by trusses set up with studs of 90x38x12x0.85 mm, in case of superior, and inferior webs, and king post, and stud profiles of 60x38x0.85 mm in case of diagonals. Above them, rafters made with structural omega profiles of 38x35x0.85 mm. In a similar way of the rest of models, a OSB cover base of 11.1 mm thick, and a PV6 zincalum steel sheet covering is suggested.

b) Finishing specifications

As flooring finishings in all models, it is suggested the use of porcelanato floor of 60x60 cm in all surfaces, and baseboards of the same material, in all spaces except for the bathroom. For all models it is proposed the use of PVC (Polyvinil chloride) thermal panels in windows.

As interior walls coating for models based on wood, and steel structures, it has been considered the use of gypsum wall board of 15 mm, and moisture resistant gypsum board for dry, and humid areas respectively. For the confined masonry model, it is contemplated in interior walls the use of stucco, and refining in dry zones, and for bathrooms only stucco as substrate for coating.

For interior walls it is used an insulation product: a mat-like polyester fiber, or technical equivalent in compliance with the corresponding Chilean norm. This type of insulation is suggested for all models.

It is proposed the use of EIFS (Exterior Insulation, and Finishing System) exterior cladding. For its installation, OSB boards from the vertical structure will be provided with waterproof coating, then polyester plates of 30 mm thick are assembled using a special elastomeric sticky paste. For finishing, it is considered the placement of a glass-fiber mesh in continuous strips using the same paste used to assemble polystyrene plates. Special granulated painting will be applied. It should be noted that this solution is presented as a finishing after the coating, erasing thermal bridges that could be present in partitions, and/or walls. [11]

In case of confined masonry model, the EIFS exterior cladding is suggested. The application of this system is similar to previous cases, but the waterproofing of OSB panels is replaced by adhesive bonding previous to polystyrene placement.

3.2 COST ESTIMATION AND GAPS

In the design proposals for different models, it was decided to develop medium-high standard solutions, in finishings, installations, and other carcass work elements such as roofing, and its base. Nevertheless, the budgets obtained can be perfectly eligible for state subsidy.

The results present final budgets ranging from US\$636.4/m², to US\$672.2/m², for 2x4" wood framing model, and the wooden post-beam model respectively. This represents a gap of 5.6% (Figure 1).

This result was expected since the post-beam system is frequently associated to high-standard solutions. What is remarkable is there is no significant differences in terms of costs, but it does represent important architectural advantages in terms of interior design modification, in respect of distribution, and area dimensions.

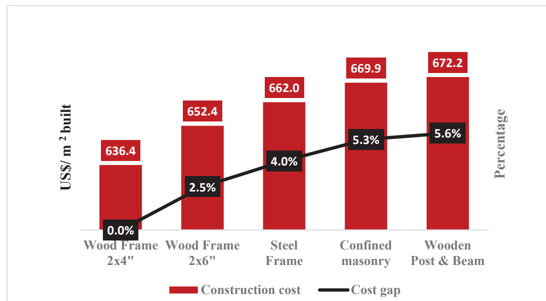

Figure 1: Final cost of construction per square meter built by model, and costs gaps.

Another interesting result is the margin difference of 2.5% between the two frame work alternatives, being the 2x6" framing the most expensive alternative. In 2x6" framing cost, the unit cost of the member used is three times superior to the 2x4" impregnated pine. The dimensions found in the market play an important roll in lowering differences in prices. The length of the 2x6" (4.8 m) allows a better use, generating scraps of only 30 cm, while in case of 2x4" member, (3.2 m) it generates scraps of 95 cm. To the better-use factor of 2x6" members, it is added the lower number of members required, due to its greater dimensions, and more distance within the frame, at the same time improving the performance in construction since there are less unions to be used.

Given the marginal cost difference of the 2x6" framing, in relation to the 2x4" framing, the evaluation of both models can be seen more as an appreciation, and comparison of these structures. Considering that the appreciation corresponds to a subjective valuation, it is assumed that clients tends to prefer more stable, and robust constructive solutions, therefore the 2x6 framing solution becomes more attractive since it presents partitioning of 18cm, which are similar to masonry walls with stucco in both faces.

The galvanized steel alternative also presents advantages in offers in terms of dimensions, with a variety of products in the market of 2.4;2.5;3.0; and 6.0 meters long.

Both wood frame models are presented as the most competitive in budget, in relation to other models using different materiality as in case of steel framing, and confined masonry. The latter is the only one who is not qualified as a dry construction, which increases execution deadlines, and project delivery.

When analyzing the cost structure of main items for each system, it is possible to verify that, due to the high, and homogenous finishings standards proposed for different projects, the cost for this concept is very similar to carcass work's, even surpassing it in case of the three models that use framing whether in wood, as well as in steels profile.

In short, big gaps among models occurs in structural cost related to carcass work. Thus, in construction of wall structures, gaps reach a maximum record of 49.8% between 2x4" wood framing model, and the wooden post-beam model, and a minimum record of 11.6% between the same 2x4" framing model, and the steel framing model. However, the maximum gap drops to 32.1% when considering the wall, and roofing as a whole, and it attenuates in 13.3% when considering the whole carcass phase. It should be highlighted that when comparing the wall structure costs, the steel framing has less costs than the 2x6" wood framing, advantage it loses when adding roofing structures, where reinforce steel has the highest cost from all the other models (Figure 2).

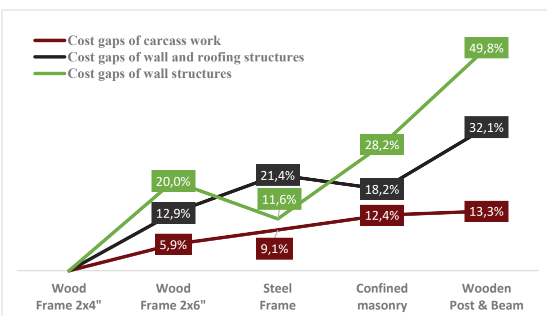

Figure 2: *Cost gaps by construction system, and project's key phases*

4 CONCLUSIONS

It is concluded that wood framing systems are competitive in relation to the use of systems based on other materials.

The estimated budgets for three wood construction models revels that it is possible to move to better standard housing projects than to the traditional ones, with prices that may be eligible for state subsidy.

This research has proved that the initial impact when comparing the unit values of analyzed wood members (2x4", and 2x6") is mitigated with design, greater use of members in works, and operational performance improvements. It is evident that a more diverse supply of products in terms of length, and dimensions, would increase wood construction competitivity.

On the other hand, the research demonstrates that is perfectly possible to incorporate other wood construction systems that may be eligible for state subsidy, and that provides greater opportunities than conventional systems. This is the case of post-beam construction system, which is traditionally associated to higher value, and size dwellings. It emerges that is feasible to develop a delimited footage project, with low cost, additionally enabling a greater use of the structural, and constructive advantages of the system in terms of interior distribution modification. It is also an attractive system for clients, and is appreciated by architects due to the possibilities it offers in terms of space, natural lighting -since it allows big openings-, and also because of the visible presence of wood in greater dimensions.

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