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Quality and Sustainability Indicators of the Prefabricated Wood Housing Industry—A Chilean Case Study

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Abstract: Wood industrialization provides a contribution to timber-based building. The Chilean market is based on attributes such as the experience and trust of companies. The sales price, meeting deadlines and quality are attributes that have motivated buyers. There are more attributes to assess that are important for the client and market country: building materials and safety, sustainability, and environmental assessment. Some of these valuations are provided by certifications such as life cycle analysis, reduction of energy, water, gas consumption, thermal, acoustic insulation, fire resistance, etc. The objective is to propose an evaluation tool using sustainability indicators for prefabricated lumber-based buildings, using technical benefits of wood as an option for manufacturing prefabricated structures. They constitute references that can be integrated with international construction standards and with it, a process of improvement of the current standards for the housing solution and protection of the environment. The methodology is based on standards compliance levels, according to current, voluntary, or referential regulations, seeking to differentiate the market offer of prefabricated homes through quality indicators, benchmarking and sustainability. The results are an evaluation model synthesized into three tables according to the category evaluated: materials, products, or structures. It concludes that, to meet demand, the market must adapt its offer to new requirements where it does matter how the housing is produced, not only in the economic aspect, but also its impact on the social aspect and the environment and what it offers in terms of quality of life. The lumber-based building sector needs sustainability attributes indicators to potentiate the companies and start a differentiation business.

Keywords: safety and sustainability indicators; wood construction; prefabricated houses; regulatory compliance; wildland–urban interface (WUI)

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Citation: Garay, R.; Pfenniger, F.; Castillo, M.; Fritz, C. Quality and Sustainability Indicators of the Prefabricated Wood Housing Industry—A Chilean Case Study. *Sustainability* **2021**, *13*, 8523. https://doi.org/10.3390/su13158523

Academic Editor: Eva Prelovšek Niemelä

Received: 20 April 2021
Accepted: 21 June 2021
Published: 30 July 2021

1. Introduction

The wood industry for the construction of prefabricated houses is becoming more important nowadays due to the properties and aptitudes of this sustainable and renewable material, providing outstanding heat insulation, ease of machining, and applicability to any climate [1]. Researchers worldwide have made enormous progress in regards to sustainability assessment instruments by using life cycle assessment systems (LCA) [2–7], for instance.

The climate impact from the construction sector has a significant role on greenhouse gas emissions, because of the raw material and energy consumption globally. The shift of the construction sector towards a circular economy is crucial to achieving a more sustainable society. According to Jockwer et al. [8], the three most effective ways to ensure the sustainable benefit of the circularity in the construction sector can be seen as: (1) maintain the service life of structures and buildings materials as long as possible to avoid unnecessary emissions and costs for demolition and reconstruction; (2) conserve the quality of materials as long as possible to avoid unnecessary emissions and costs for the replacement and processing of new materials and (3) recycle and repurpose only the parts and materials which cannot function anymore for technical and/or socio-cultural reasons.

Among common construction materials, rough sawn lumber has a long tradition of numerous applications as a renewable material, thus the implementation of the concept of circularity in the process of the construction of lumber buildings has a high potential sustainability impact when the lumber is sourced from sustainably managed forests [9].

Lumber exhibits a slow and predictable burning process, and the charring creates a protective layer that slows down the progress of fire. Nevertheless, there is a need to study new types of timber buildings made from, e.g., CLT (cross-laminated timber) in terms of fire resistance. Insurance companies are often critical of the fact that the fire safety rules are too weak in terms of the protection of property, even though they save lives. Since damaged property constitutes great costs for them, they would like to see stricter regulations. In the case of a fire, in their experience, the damage is likely to be more severe and extensive if the building is wood-based rather than a concrete building [10,11].

Furthermore, the environmental indicators to be considered are those defined in ISO 21931-1 [12], such as process quality of maintenance, waste production and disposal, reuse, recycling, recovery of materials and repair, conservation, and replacement of products used in the building. Energy consumption is the most relevant aspect of the processes, except in the case of design for assembly (DFA) approaches.

Latin America has a population of 624 million and presents high rates of urbanization, with over 80% of this population living in cities (GlobalABC, IEA and UNEP 2020) [13]. Most cities in the region face challenges like urban sprawl and fragmentation, lack of public infrastructure, expansive areas of informal settlements and a high percentage of the population living in inadequate housing, located in vulnerable areas. This is aggravated by the high levels of informality in the construction sector, with self-construction being a common practice.

The life cycle sustainable assessment (LCSA) framework has been successfully applied worldwide to buildings made of a wide range of building materials, such as recycled materials, industrial by-products, virgin materials, and to demonstrate how the integration of service life estimation of the building and building components affect the TBL sustainability performance of residential buildings [6].

Chile is moving towards establishing public policies to ensure that the construction market adopts sustainability criteria: instruments such as energy rating of homes, certification of sustainable buildings, certification of sustainable homes, measurement of carbon footprint in buildings (WHICE), and recently a certification of sustainable housing (CVS) is evaluated, but most of them are still voluntaries rather than mandatories. All these public policies are centralized by the Ministry of Housing and Urban Planning (MINVU) [14–21], with gradual incorporation of initiatives. The Chilean wood construction sector is barely integrated, due to its high fragmentation, and is now controlled by only the most advanced and benchmark companies in the market, which have superior economic and technological capabilities. In the prefabricated wood construction sector, there are different business models, and there are some companies that carry out sophisticated processes, even acting as real estate companies providing turnkey housing solutions, while others are architecture offices that cater to the private housing market. By default, most are housebuilders; they do not participate in the urbanization, assembly and finishing processes. Moreover, there are sustainable construction standards that are voluntary, and so the same happens with the housing certification evaluation instrument, which follows global trends [2] regarding the criteria that are evaluated (health and well-being, energy, water, materials and waste, environmental impact, immediate surroundings). However, these instruments do not impact, or do so to a limited extent, the wood construction sector, due to the high variability of construction typologies and business models, where some manufactures build without any regulation or standards. Therefore, this study seeks to establish more specific criteria to try to make the sector self-evaluated by a simple and easy-to-use tool in terms of processes and products, which allows the wooden industries to implement this proposed instrument to differentiate their offer in the market, making them more competitive.

Wooden house buildings are produced at different quality levels, ranging from extremely precarious homes to others that are extremely comfortable and sophisticated. In this range, timber and wooden frames allow great versatility, resulting in materials with an excellent cost–benefit ratio, efficiently offering the most vulnerable aspects such as high durability, low susceptibility to termite attack, and fire resistance [17,22,23]. The quality of the material is not what determines the constructive typologies, so it is perfectly possible to reach high standards [22].

Livability should basically ensure that a building provides the minimum habitability conditions [23,24]: water and air tightness, seismic design of components, acoustic and thermal standards established in the thermal regulation following Technical Standard NTM 001 of the Ministry of Housing and Urban Planning (MINVU) [18,25] to fire regulations, outdoors conditions, and resistance to biotic and abiotic degradation. One special issue is the fire resistance of wooden buildings. At a national level, there are mandatory regulatory requirements for fire resistance, present in the OGUC [26] for building components. In the case of wooden housing, improved wooden elements produce upgraded wooden structures, thus the safety and sustainability aspects are enhanced for this type of construction [21]. A scheme showing the progress in Chile is shown in Figure 1 according to the government-driven buildings sustainability initiatives from 2012 to 2016 [15].

In order to use a building component solution with a wooden framework, which is not specified in the MINVU list, there is a need to incur extra expenses and time, so that the element has the corresponding support, fulfilling the requirements of current regulations regarding fire resistance [27]. Quality is defined as a set of properties inherent to an object that gives the capacity to meet the implicit or explicit needs of the consumer [28]. There are several ways to meet these needs, even more if there are possibilities to access higher standards; the market should generate an offer in an opened and informed way, trying to improve properties that guarantee greater efficiency, comfort, durability and other qualities.

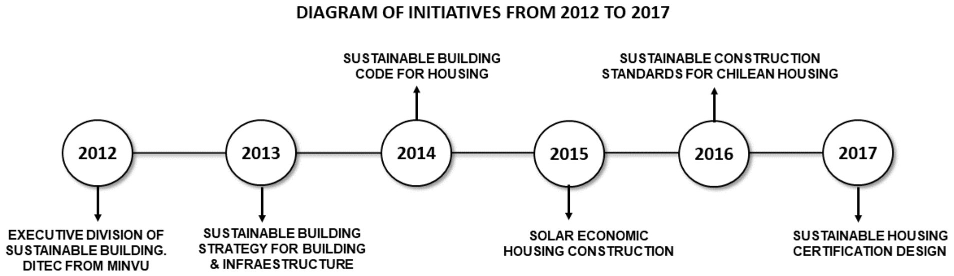

Figure 1. Sustainability initiatives in government-driven buildings from 2012 to 2016.

A possible way to adopt upgrading building standards is through updated technical standards and technologies and machinery that contribute to achieving efficient and innovative processes and products, equilibrating competitors to meet the needs in this sector. In the public sphere, establishing mandatory regulations may generate an adaptive transformation if it is supervised and progressively put into action. On the other hand, in the private market, these requirements are not always adopted because the market does not exert pressure. Therefore, another option is to compare products and processes through indicators that discriminate attributes that add value to the products.

The model design by Zubizarreta (2019) [29] is applicable to several countries developing timber-based buildings. Although it has been applied and tested in the Spanish construction sector, its application to buildings located in other countries would require the formation of a national expert panel to analyze the specific characteristics of the timber-based construction sector and process the information for adapting and adjusting the indicators and criteria. This is a necessary stage, since the researched criteria are extremely dependent on the characteristics of the construction sector at a national level.

Another relevant study on the selection of sustainable urban development evaluation models was conducted by Gil and Duarte (2013) [30]. They concluded that it is difficult to find a tool as the "ideal one", since the choice is not easy and that there are still possibilities for improving the existing tools, as well as the possibility to develop new tools. The authors affirmed that a complete standardization of the different evaluation models is neither possible nor desirable because the models can include design principles that cannot be accepted universally. Those models might require data that are not available in the local scope and can include indicators without relevance to any specific context, whether geographic, policy or project-related.

Globally, the most used certifications are LEED, BREEAM, PassiHouse, DGNB, and EDGE. However, there are many regional and national level standards that are being applied, such as the newly developed CASA certification in Guatemala, the Estidama Pearl Certification in the UAE, Green Star in Australia, the Living Building Challenge 4.0 Standard (USA; with global scope) or Greenmark in Singapore. There are also regional rating systems, such as the Global Sustainability Assessment System (GSAS) in the Middle East or the Green Building Index (GBI) used in Southeast Asia.

According to these antecedents, the main objective of this article is to propose an evaluation tool using sustainability indicators for prefabricated lumber house buildings that are marketed in Chile, analyzing the main technical benefits of wood as an option for manufacturing prefabricated structures, and considering the different manufacturing standards present in Chile. They constitute references that can be integrated with international construction standards as a process for improving the current standards for the housing solution and protection of the environment.

2. Materials and Methods

The development of the tool used in this study was based on criteria defined by May et al., 2017 [31], Danso et al., 2013 [32] and Danso, 2018 [33] with slight modifications to fulfill Chilean standards. Moreover, this study seeks to assess through three indicators: (1) quality indicators; (2) benchmarking indicators and (3) sustainability indicators to evaluate three main categories for prefabricated wooden houses. The aim is to develop a simple model for those manufacturers that do not yet have access to certification systems and require sustainability indicators to prepare improvement plans for their products and processes. The three categories to evaluate according to the indicators mentioned below are wood elements, wood products, and wood structures.

For quality indicators, the reviewed and selected attributes are summarized and described in Sections 2.1 and 2.2. The benchmarking indicators are included in Section 2.3, since they are relevant to motivate the industry to evaluate a system under continuous business improvement in terms of management, production, and products. Among the sustainability indicators, the environmental, economic, and social attributes were selected and explaining in Sections 2.4–2.6.

The design of this study considers developing a tool based on Likert scales for attributes and indicators to discriminates between the prefabricated housing products existing in the market. Twenty-five indicators were identified and selected, from these eleven indicators correspond to the environmental dimension, eight to social dimension and six to the economic dimension These indicators are shown in Figure 2, where it is possible to observe the hierarchical structure of this tool for the evaluation of the sustainable construction materials. For all indicators, a five-point Likert scale was used to define the levels adopted by each key indicator, which ranged from unimportant (1) to very important (5). Therefore, the manufacturers will count on a self-evaluation to identify key aspects of their wooden processes.

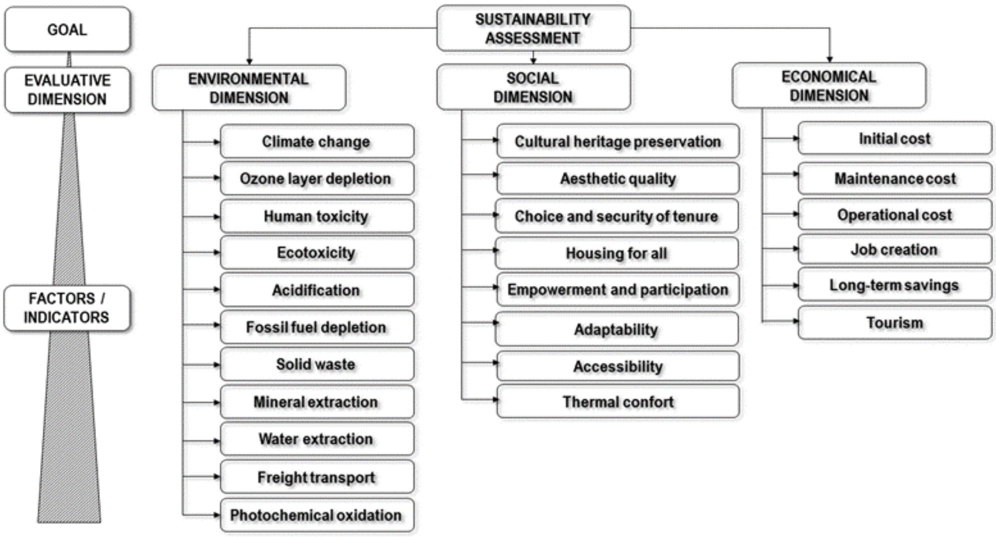

Figure 2. Hierarchical structure for construction material sustainability assessment.

2.1. Regulatory Requirements for Wood Elements

The European building regulations are generally being altered towards functional or performance criteria, rather than being prescriptive. This development was accelerated by the Construction Products Directive (CPD). The implementation of the CPD has opened the European market for building products. It has also facilitated the use of multistore wooden buildings in many countries [34]. From this, there are two strategies we must pay attention to: there is a standard of homologous construction systems among European countries and there is also a commission in charge of promoting wood development in the region and the evaluation moves towards performance rather than prescriptive. The CPD regulations are interpretive documents based on technical European standards with harmonized methods for verification and building safety. The new European harmonization of standards will hopefully provide more common national regulations. This process is complicated, and the velocity of implementation (voluntary or regulated) varies among countries.

The residential buildings constitute a major element of the construction industry contributing significantly to environmental deterioration directly or indirectly according to the global report published by the Energy Agency (IEA) [13].

The Chilean regulatory framework mainly addresses the following technical criteria: fire resistance, acoustic performance of elements, thermal insulation of construction elements, regulations for structural and seismic stability, and specific regulations related to the use of wood in construction and updating of national standards. Regarding these technical standards, the Ministry of Housing and Urbanism (MINVU) establishes their use through the documents included in the so-called OGUC and Supreme Decree No. 10 (DS10). The standards related to wooden constructions are Nch789/1 (1987), NCh819 (2012), NCh1198 (2014), NCh1970/1 (1988), NCh1970/2 (1988), NCh1989, NCh1990 (1986), NCh2151 (2009), and NCh2165 (1991) currently under review and update, NCh176/1 (2003), NCh1207, NCh631 (2003), NCh763/1 (1996), NCh763/2 (1996), NCh755 (1996), NCh2148 (2013), NCh2150 (1991), NCh723 (2004), and NCh819 (2012). In summary, all the lumber intended for structural use must meet requirements regarding dimensions and tolerances, durability, moisture content, and structural classification.

More specifically, the requirements for building horizontal frameworks from sawn lumber or planed timber are a moisture content level under 18%, they must be impregnated (as establishes on NCh 819), they must fulfill structural grade G1 or G2 (according to NCh 1270 and NCh 1198 1 and 2), depending on the structural calculation [22]. These norms and standards define technically for example that in diaphragms it is possible to use plywood or OSB where thicknesses will depend on a set of technical criteria (thermal and acoustic insulation and fire resistance), in addition to the structural requirements, normally using thicknesses of 11 to 15 mm.

2.2. Regulatory Requirements for Wooden Structures

The utilization of LCSA for assessing environmental, social, and economic aspects of sustainability of the building industry is a relatively new area of study. Several studies highlight the recent developments in countries around the world about the utilization of wood as a construction material [35–38]. These initiatives are specially regulated to accomplish fire safety standards.

Currently, the regulations are renovated and updating mainly due to concerns about environmental issues and the COVID-19 pandemic. In terms of buildings, there is a movement to design buildings more energy efficient. For this, the Japanese Ministry of the Environment developed an online platform on Sustainable and Resilient Recovery from COVID-19 (REDESIGN 2020). Another example is the effort done by the Institute for Global Environmental Strategies (IGES). These actions including the commitments by the European Union in the Renovation Wave, The United Kingdom and its public sector and social housing decarbonization for supporting public housing and public buildings.

In order to diminish the human impact on the environment, many countries have accepted the Nationally Determined Contribution (NDC) guidelines, which bring a significant opportunity to integrate specific mitigation policies for buildings and to make use of codes, standards, and certification that drive the sector towards zero-carbon emissions. Therefore, the timber construction sector can maximize benefits, with clean production processes, with improved products measured in their LCA, taking into consideration the advantages of wood towards industrialization that meets the sustainability criteria that the planet needs.

Certification of a building's energy and/or sustainability performance highlights improved practice construction efforts and provides a market signal to sustainability-conscious investors, tenants, policymakers, or consumers. Green or sustainable building certifications play an important role for building developers and owners to distinguish their buildings within the market [13].

In Chile, as in many countries in the world, the certifications have been adopted for buildings based on sustainability criteria [35], few are included in mandatory regulations, others are voluntary [19], and they are independent of the type and construction materiality. For example, the Ministry of Housing and the Ministry of Energy are adding life cycle assessment evaluation (LCA) to new housing, also independent of the type and materiality built, putting emphasis on the use of sustainable resources, adding BIM systems for the design and inclusion of sustainability criteria to the validation of these buildings. However, the dispersion and poor cohesion do not contribute to cover the necessary advance of all the subsectors at the same time or at the same speed. Therefore, the tool design here will bring new possibilities to improve the quality and value of wooden structures.

Although there is a political will to promote the use of wood in high-rise buildings, certain stages have yet to be completed, such as having local CLT production capacity, strengthening fire resistance regulations, establishing conditions for companies to operate insurance, and provide sufficient guarantees to users to accept these constructive solutions.

For the development of this tool, we understand that only those companies who find favorable integration routes will react and join in, while others will be left behind by doing the same as always, due to lack of access to information, being poorly agglutinated, or simply because the trend is focused on innovation where they do not see the possibility of integration. This makes the performance evaluation models sustainable, free, easy-to-use that will motivate them to improve processes and products. For these segments, it is intended to initiate differentiation actions, since they have always been built in wood and their adoption of changes is made by virtue of what the market demands, and due to regulatory requirements. This work seeks to be an initial opening proposal to motivate the industrialized construction productive sectors, who through a tangible analysis of the differences can add value to their offer, initiating a continuous improvement based on competencies and demonstrable attributes of their products, to participate in certification processes and compete in that space with other construction typologies and other materiality. This instrument allows them to know and differentiate what they do and thus evaluate themselves.

The building industry is one of the sectors, generating the greatest impact on the environment [36], due to the large number of resources consumed during the execution process and throughout its useful life. In Chile, the materials used in building structures are mainly reinforced concrete and masonry, leaving the wooden construction relegated to lower structural use, mostly being used in finishing works [21,22,37–39].

For the development of this tool, we established the regulations found on OGUC guidelines, which establishes the minimum conditions for building elements not subjected to stability calculation, indicating that the house can be built up to 3 floors and with a maximum height of 7 m. Moreover, these guidelines dictate the values for the maximum thermal transmittance (U) or the minimum total thermal resistance (Rt) for ventilated floors, walls and roofing depending on the climatic zone in Chile, as shown in Figure 3.

The analytical determination of those parameters is specified in NCh 853 and NCh 851. It can be performed by calculations or using insulating materials labeled R100, as specified in NCh 2251. In addition, it is possible to incorporate constructive solutions from the Official List of constructive solutions for thermal conditioning made by the Ministry of Housing and Urban Development [40].

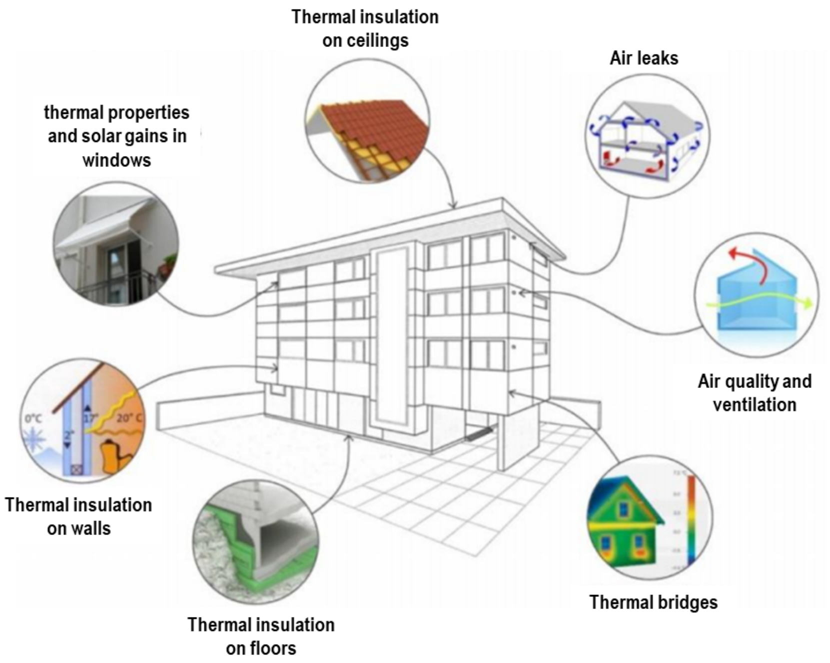

Figure 3. Requirement of thermal conditioning.

In terms of fire protection, this study used the requirements indicated in OGUC [26] Title 4, Chapter 3. Houses must be built in accordance with Table 1. The letter F followed by a number expresses in minutes the capacity exhibited by a building element to preserve its mechanical stability, flame tightness, thermal insulation, and non-emission of flammable gases. The tests to determine the fire resistance of the construction elements are specified on NCh 935/1. These requirements are also applied to extensions built on the houses.

Table 1. Requirements for fire protection.

Type	Walls Divisors between Units (Until the Cover)	Vertical Support Elements	Non Supporting Walls and Frames	Stairs	Horizontal Supporting Elements	Skirt Included False Sky
3-floor homes	F-60	F-60	–	F-15	F-60	F-30
Houses of 1 or 2 floors	F-60	F-30	–	–	F-30	F-15
Housing up to 140 m—1 or 2 floors	F-60	F-15	–	–	F-15	F-15

In terms of acoustic insulation, this study followed the guidelines established on OGUC Article 4.1.6 for dividing elements or separators of housing units.

The horizontal or inclined construction elements, as well as vertical or inclined elements used as dividing walls, must have a minimum acoustic reduction index of 45 dB (A) and have a maximum impact sound pressure level of 75 dB. Unions and meetings between different materials must comply with the same specifications indicated above.

For compliance, there are two ways: using the official list of constructive solutions of the Ministry of Housing and Urban Planning or through tests of the acoustic reduction index based on the NCh 2786 standard and acoustic impact pressure according to ISO 140-6 and ISO 717-2 [41]. The tests must be carried out by authorized laboratories registered in the Official Registry of Quality Control Laboratories of the MINVU.

It is worth mentioning that radiata pine wood can be used as structural material if it is preserved because this type of wood is classified as "non-durable" as specified in NCh 789/1. Radiata pine is the most used species in the Chilean market because of its easy industrialization. Other species identified as wood constructive materials are presented in Table 2 and categorized according to the expected use and risk.

Table 2. Expected use and risk.

Cat	Classification	Expected Life	Species
1	Very durable	$\geq$20 years	Nothofagus obliqua (Roble) Pilgerodendron uviferum (Ciprés de las Guaitecas) Fitzroya cupressoides (Alerce)
2	Durable	$\geq$15 years	Nothofagus alpina (Raulí) Nothofagus pumilio (Lenga) Persea lingue (Lingue)
3	Moderately durable	$\geq$10 years	Drimys winteri (Canelo) Nothofagus dombeyi (Coigüe) Weinmannia trichosperma (Tineo) Eucryphia cordifolia (Ulmo)
4	Few durable	$\geq$5 years	Araucaria araucana (Araucaria) Eucalyptus globulus (Eucalipto), Laurelia sempervirens (Laurel) Podocarpus nubigenus (Mañío)
5	Not durable	$\leq$5 years	Populus sp (Álamo) Aextoxicon punctatum (Olivillo) Pinus radiata (Pino radiata D. Don) Laureliopsis philippiana (Tepa)

2.3. *Attributes Differentiating and Benchmarking*

Nowadays, companies should demonstrate their ability to direct the business towards the customer. This implies identifying the differentiating factors of the process, product, or management of the referent to create a product improvement plan for its adaptation to a more demanding market.

Green buildings represent one of the biggest investment opportunities of the next decade, accounting for USD 24.7 trillion across emerging market cities by 2030 [42]. Cities in emerging markets are expanding at a fast pace to keep up with high population growth and rapid urbanization. Further, according to the World Resources Institute, there is a shortfall around the world of 330 million homes, which is expected to jump to 440 million homes by 2025. This means that the investment opportunity is mostly in new residential buildings, which are valued at USD 15.7 trillion and represent 60% of the total market [43].

The proposed management tool will be useful to improve the practices and procedures for the wood construction companies, since they can compare each other under the same indicators, also it will allow them to improve and grow. In this way, the results obtained after applying this tool can be used as a differentiating attribute for the manufactured product, thus the organizations will be able to demonstrate their capacities in the different evaluated areas and their applications. Therefore, the proposed tool is based on the benchmarking process shown in Figure 4.

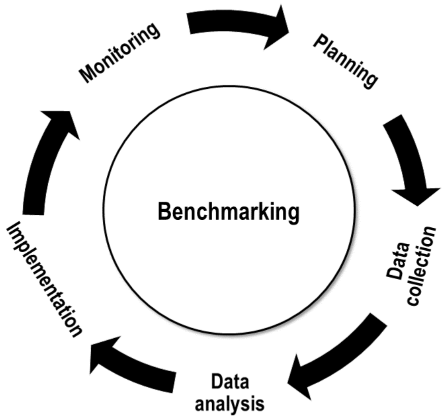

Figure 4. Scheme of the benchmarking phases.

As an example of benchmarking, Canada developed the Wood First Program to encourages the forest industry, researchers and design professionals to explore innovation in B.C.'s built environment and through value-added wood products, helping to grow local and global markets, while promoting climate-friendly construction and supporting our forest-dependent communities. Another initiative is to quantify the benefits of building with wood. Evaluate the carbon footprint of wood buildings with this online tool.

2.4. Sustainability

In the study published by May et al. (2017) [31], the authors recommended a combination of indicators from all three aspects of the PSR framework for a holistic environmental assessment of wood products. We cannot say there is an ideal combination of indicators and methods because this would first require an investigation on the maturity of indicators with respect to criteria, such as practicability and ecological effectiveness, for the local wooden construction sector. Nevertheless, we consider our overview as a first step towards closing the research gap in this area. Concerning the proliferation of efficient and environmentally beneficial wood products, a subsequent step could be a comparative, extended life cycle assessment of wood products within a common scope but differing in their origin of the forest resource, tree species, production technology, end-of-life, and technical aspects such as weather resistance, according to several studies [3,5,37]. Then, despite the overwhelming distance between the sustainability evaluation of the Chilean wood construction industry and the world [8], we present a selection of criteria to be considered as an important differentiation in the market.

The results of Padilla and Balnchet [44] confirm the positive effect of using the prefabricated approach in buildings as an alternative construction method based on wooden-frame materials in Quebec. By using the CO2 emissions as a global indicator, the climate change impact (CC) saving per m2 floor area in the baseline scenario produces up to 25% fewer emissions than traditional buildings. If the benefits of low carbon strategies are included, the wooden structures can cause up to 38% lower CC than the original baseline scenario. The analysis suggests that CO2 emission reduction in the construction of buildings as climate change mitigation is perfectly feasible by following different working lines. We concluded that the four strategies implemented have an environmental benefit in reducing greenhouse gas emissions. The reuse of wood waste into the production of particleboard has the greatest environmental benefit when considering temporary carbon storage.

In Chile, there are codes for sustainable construction [17], although they are voluntary at the moment. The Code of Sustainable Building for Housing is a guide to good practices to improve the environmental performance of homes, using objective and verifiable criteria. It is a national Code to be used in the design and construction of housing or in renovated homes, and to promote continuous improvement in sustainable construction. The Ministry of Housing and Urban Planning (MINVU) oversees this Code. The Code [17] covers four main categories of sustainability: Energy, Water, Waste, Health and well-being. It also includes several additional topics besides the four main categories, which were grouped into a category called “Other”. Although this is an effort of the state apparatus (see Figure 1), in the private field of wooden construction, it is difficult to find evidence that they have incorporated these guidelines into the market, possibly due to its recent and voluntary nature, which does not offer motivational tools of adoption.

2.5. Key Environmental Indicators Processes and Products

The environmental impacts caused by current production and consumption models coupled with the current economic situation show that the industry has to move towards more sustainable business models to adapt to changes in legislation and market trends [45].

The current production processes have caused environmental problems with a direct impact on the economy and society due to an increase in waste generation, atmospheric emissions and discharges as well as excessive consumption of resources that is causing the degradation of natural ecosystems [46].

Although these changes can be an effort for companies, since in many cases it requires changes in the product and/or the production process [46], a move towards more sustainable development models is an opportunity for companies to stimulate their innovation, create new economic perspectives and improve their competitiveness, in addition for improving their environmental behavior. That is why sustainable innovation emerges as a strategic option to improve competitiveness in the industry.

2.6. Key Economic Indicators

Experts from prefabricated wooden housing [47–50] pointed out that wooden buildings are not cheaper than using other materials, such as brick or concrete. The reason they argued is that the structure costs can be relatively cheaper, but achieving mandatory regulatory specifications, such as thermal comfort, sound insulation, dry and wet network, among others, leads to increased costs. Moreover, it is a mistake to build homes without these built-in attributes since its subsequent inclusion will imply higher costs than doing it at the beginning of the work.

Then, the house should not only consider the costs of building, but also the maintenance costs, that is, operating expenses which, for example, will be higher if the house does not have thermal insulation or if it later needs finishing works as interior linings and external protection. So economic indicators should consider at least five indicators as key economic factors of sustainable building materials. They are maintenance costs, operating costs, initial costs, long-term savings, and useful life [32,51].

In our model, we assume that the maintenance cost of construction components is the cost involved in the process of maintaining the performance of a home and its operational needs. This process involves a set of activities that are useful to maintain the components of a home. The operating costs include payments such as mortgage, construction insurance, taxes, repair costs and other administrative expenses.

Additionally, the initial costs, which are those that people with fewer resources usually exclusively consider in their purchase decision, are the costs of the design and construction process, exclusively affecting the sale price of the home without considering the expenses of land authorization, urbanization of the environment, acquisition of land, etc. In terms of the acquisition of prefabricated houses, the condition usually does not include installation costs, transportation and enabling sanitary, electrical or gas networks. The proportion of turnkey options—where companies do offer this complete service—is less. In case it happens to be so, the responsibility of the installation is transferred to the company (possibly also the registration and reception of work by the corresponding authorities), which is an important aspect in relation to administrative costs. The initial cost of the construction project includes the cost in the following construction stages: planning, design, and construction.

Long-term savings are essential to reduce the operating cost of any structure, materials, and construction components. While some sustainable materials may require higher initial costs, they bring long-term savings due to reduced energy and transportation costs, as well as being beneficial for the long-term environment.

2.7. Key Social Indicators

The key social indicators have been classified for sustainable building materials according to several studies [33,35]. The first selection of indicators to be qualified was: adaptability, thermal comfort, preference for local resources and housing for all. Other indicators suggested, but not incorporated in this protocol, are cultural heritage, social value, choice and security of tenure, accessibility, empowerment and participation and aesthetic quality, which have been investigated by Danso, 2018 [33]. Adaptive housing is defined as "dynamic systems that allow the ability to accommodate a set of evolving demands with respect to space, function and components" [52].

Buildings that cannot adapt to such changing needs will become obsolete or require substantial renovation or demolition, where no option can create a sustainable built environment. Building materials contribute greatly to the thermal energy and comfort of any structure.

Adaptive thermal comfort is extended to the understanding of the human comfort zone considering the ways in which people's perceptions of their environment change according to seasonal expectations of temperature and humidity. It is an undeniable fact (especially in warm weather areas) that houses built with local materials have a cool ambient temperature, particularly those houses built with earth or earth and straw, although this contrasts with seismic resistance requirements [53].

Therefore, it is important to integrate the necessary technical criteria when selecting building materials based on local resources (materials such as sand, stones, grass, straw, clay, wood, clay bricks and clay blocks) available and affordable in most locations, especially in developing countries to meet their housing demand.

"Housing for all" is a concept that describes the situation of ensuring an affordable and available house to everyone. Therefore, housing for all is associated with affordable or low-cost housing. According to the report presented by United Nations Human Settlements Programme 2015 [54], affordable housing has been defined as a house that is adequate in quality and location and does not cost so much that it prohibits its occupants from covering other living costs and threatens the enjoyment of basic human rights.

On the other hand, the United Nations [55] analyzes the housing deficit, indicating that 1.6 billion people live in inadequate housing, among which one billion reside in slums and informal settlements. The UN carries out worldwide campaigns highlighting the

"World Habitat Day with affordable housing" and promotes housing policies to guarantee the affordability of housing. Therefore, it assumes a complex issue of strategic importance for development, social peace, and equality, in which Chile and its timber construction industry can make a great contribution.

The concept of affordable housing for all implies that the total cost of purchase or rent a house allows access to those with average income, including the cost of materials, the cost of labor, the cost of land, among others. The cost of building materials is between 60% and 70% of the total cost of a building in developing countries [32]. Therefore, the reduction of the cost of the material helps in the promotion of housing for all. However, it is the job of the State to safeguard that the dwelling does not become insecure and precarious, striving to guarantee a minimum standard that provides security and sustainability.

Danso, 2018 [33] concludes that key factors in discerning environmental sustainability are: human toxicity, climate change and solid waste. Adaptability, thermal comfort, local resources, and housing for all are identified as the four key social indicators. The initial cost, maintenance cost, operating cost, long term, savings and useful life are the five key economic indicators to measure sustainable building materials. Therefore, an evaluation of sustainability in wood construction should consider, at the very least, these 12 attributes.

Taking an example, the Urban and Territorial Planning for Sustainable Development of the International Guidelines on Urban and Territorial Planning of United Nations Human Settlements Programme has established the following principles: (a) Urban and territorial planning primarily aims to realize adequate standards of living and working conditions for all segments of current and future societies, ensure equitable distribution of the costs, opportunities and benefits of urban development and particularly promote social inclusion and cohesion; (b) Urban and territorial planning constitutes an essential investment in the future. This effort considers that a precondition for a better quality of life and successful globalization processes is achieving by respecting cultural heritage and cultural diversity for the recognition of the distinct needs of various groups.

Chile is working on several sustainable development objectives, modifying the regulations to build with wood materials, but the territorial planning gaps have yet to be focused on not only to build sustainably but also safely [56–58].

3. Results

Although the sustainability evaluation proposed was developed for the Chilean market, this model can be adapted to be used in any country according to their regulations. It is important to clearly focus on reconstructed wooden housing.

The Chilean government is working on establishing public policies to ensure that the construction market adopts sustainability criteria not only related to energy savings but also to those attributes and indicators investigated in this study. A certification of sustainable housing (CVS) is being created, for which a registry of evaluators and a registry of projects that qualify for this voluntary certification are opened. Consequently, the wood construction sector needs to join by incorporating differentiating indicators of its sustainability attributes, such as the proposal presented in this research.

3.1. Benchmarking, Sustainability, Quality and Price Indicators

In Chile, the following gaps were identified in the Strategic Wood Sector (SME) of the Maule Mesoregion, Bio Bio, La Araucania and Los Ríos: lack of scale in all links of the productive chain; lack of associativity between SMEs to improve the standard of wood quality; access to incorporate new drying technology; guarantee supply at agreed times and at a competitive price; there is no link with target market: production–design [59].

This work seeks to contribute with market intelligence, since a change of perception and valuation paradigm is required by the end customer. The existence of an evaluation that discriminates when there is value added and when there is none, based on attributes of interest that are easily understood by customers and suppliers. The reason is that, on many occasions, the wood is used in emergency housing, or precarious prefabricated solutions [60] as opposed to well-executed engineering solutions [61,62].

Sustainability integrated into the marketing strategy can become an opportunity for prefabricated housing companies to achieve a competitive advantage.

Therefore, the inclusion of the marketing concept (presented in Table 3) as the main key indicator is recommended, as this allows extending compliance towards future needs based on creating, communicating, and delivering value and sustainability to the client.

Table 3. The transformation of traditional 4P (Product, Price, Place and Promotion) to 4C, that is, Solution for the client, Cost for the client, Comfort and Communication.

Traditional Marketing Mix		Sustainability Marketing Mix
4P		4C
Product	TRANSFORMATION	Customer Solution
Price		Customer Price
Place		Convenience
Promotion		Communication

Thinking on what happens in the planning and decision-making of a productive sequence, we incorporated value attributes that explain why sustainability in processes is important, in addition to classic quality and price attributes [28].

By incorporating new criteria and indicators, the market can be strengthened, making the evaluation more specific for different single cases [59,63].

This study incorporated a selection of indicators [31,33], and decided to separate them into two groups, this is products and processes.

First, the products are presented, followed by the processes, organizing both groups according to three regulatory compliance criteria: Materials, Construction Elements and Structures. The considerate attributes were sustainability (in its three levels: environmental, economic, and social), quality and price, following our findings from previous studies.

3.2. Attributes and Indicators

The aim of the proposed tool is to collect information about how manufacturers perform their processes and how to improve according to the results of this self-evaluation. Therefore, Tables 4–6 show the selected indicators for each attribute. This proposal includes the Likert scale from 1 to 5 for each indicator, where 5 represents the highest level, 4 is medium-high, 3 is medium, 2 is medium-low, and 1 is low for each concept or criterion under evaluation.

The evaluation model aims to determine ranges of levels for the indicators, for example, as based on the initial step of WUI criteria, i.e., IFC has learned that green buildings should be certified as green under one of the internationally recognized certification standards or an approved national standard. When IFC provides a point for green building, it requires eligible products to be certified and at least 20% more energy efficient than the benchmark. After this evaluation is carried out, it will be possible to inform features such as the type of green certification system applied; green floor space; reductions in energy, water, and energy embodied in materials against a benchmark; and reductions in carbon emissions. For residential projects such as low-income housing, additional metrics include the number of households or people affected.

A prefabricated house was used as a model of the proposed methodology and the results are presented in Table 4.

Table 4. Materials Attributes and indicators.

Category A: Products: from Materials or Individual Construction Elements Considered Raw Materials to Be Transformed into Construction Elements by Themselves or as Part of More Complex Structures such as Prefabricated Modules and/or Homes: Eg Structural/Non-Structural Wood, Boards of Different Types for Prefabricated Houses							
Regulatory Compliance with Sustainable and Quality Materials	**Evaluated Attribute**	**DESCRIPTION**	**Scale**				
			1	**2**	**3**	**4**	**5**
SUSTAINABILITY	ENVIRONMENTAL	The selected indicators for the environmental attribute of product sustainability compliance are: 1. It has environmentally distinct distinguishing characteristics, by measuring and communicating its footprint of ecological, water, clean production; 2. Complies with regulations on technical aspects for the use of wood in construction; 3. The wood is preserved with preservatives of low toxicity; boards, use low or zero-emission adhesives; 4. Safe and effective treatments against degradation; 5. Wood comes from environmentally certified forests (CERTFOR, FSC, PEFC, etc.); 6. Shows a productive chain with a commitment to sustainability (Chain of Custody Standard); 7. Indicates CO2 sequestration.					
	ECONOMICAL	The indicators selected for the economic attribute of product sustainability compliance are: 1. Its production is lasting over time; 2. It can be considered a renewable and ecologically acceptable resource.					
	SOCIAL	The indicators selected for the social attribute are: 1. It contributes to generating employment (quality work development); 2. Complies with labor regulations; 3. Its use and commercialization do not generate social conflicts (Sustainable Forest Management that applies to forest owners).					
QUALITY	RATING	The indicators for the rating or labeling attribute are: 1. The product has labeling or equivalent that guarantees having undergone a classification process; 2. Its characteristics, properties and grade are relevant to the specified use; 3. When performing classification, it is possible to verify compliance with dimensional requirements, moisture content, type, and number of permissible defects.					
PRICE	COST–BENEFIT RELATION PRICE QUALITY RATIO	Price quality ratio indicators: 1. They must have technical specifications that allow their valuation by the market, understanding that different qualities and prices can meet different needs 2. The information allows an informed choice					

Table 5. Products attributes and indicators.

Category B: Products: From Materials or Individual Construction Elements Considered Raw Materials to Be Transformed into Construction Elements by Themselves or as Part of More Complex Structures such as Prefabricated Modules and/or Homes: Eg Structural/Non-Structural Wood, Boards of Different Types to Prefabricated Houses.							
Regulatory Compliance with Sustainable and Quality Elements	**Evaluated Atribute**	**DESCRIPTION**	**Scale**				
			1	**2**	**3**	**4**	**5**
SUSTAINABILITY	ENVIROMENTAL	The selected indicators for the environmental attribute of product sustainability compliance are: 1. It has environmentally differentiating characteristics, for example: measures and communicates its carbon and water footprint; clean production; 2. Its components (wood or other) are preserved with low toxicity preservatives; boards use low or zero-emission adhesives; 3. Safe and effective treatments against degradation; comes from environmentally certified forests; 4. Other components such as fasteners, connectors, joints, adhesives, and isolating materials are evaluated according to similar characteristics; 5. Complies with current environmental regulations, eg. the building components come from forests with a current management plan approved by CONAF.					
	ECONOMICAL	The indicators selected for the economic attribute of product sustainability compliance are: 1. Its production is lasting over time; 2. It can be considered a renewable and ecologically acceptable resource.					
	SOCIAL	The indicators selected 1. It contributes to generating employment (quality work development); 2. Complies with labor regulations; 3. Its use and commercialization do not generate social conflicts (Sustainable Forest Management that applies to forest owners).					
QUALITY	RATING	The indicators selected 1. Its characteristics, properties and grade correspond to the specified use; 2. When performing classification, it is possible to verify compliance with dimensional and moisture content requirements, type, and number of admissible defects.					
PRICE	COST–BENEFIT RELATION PRICE QUALITY RATIO	The indicators selected 1. Price quality ratio indicators: 2. They must be specified with their respective technical data sheets; 3. They allow the value differentiation between seemingly equal products, but with different properties.					

Table 6. Structures attributes and indicators.

Category C: Products: from materials or individual construction elements considered raw materials to be transformed into construction elements by themselves or as part of more complex structures such as prefabricated modules and/or homes: Eg Structural/Non-Structural Wood, boards of different types to prefabricated houses.							
Regulatory Compliance with Sustainable and Quality Elements	**Evaluated Atribute**	**DESCRIPTION**	**Scale**				
			1	**2**	**3**	**4**	**5**
SUSTAINABILITY	ENVIROMENTAL	The selected indicators for the environmental attribute of product sustainability compliance are: 1. It has environmentally distinctive differentiating characteristics; it has environmental certifications or evaluations of some kind. 2. Matches voluntary sustainable building codes or eg measures and communicates its energy efficiency, active or passive fire protection. 3. Communicates actions such as measuring carbon or water footprint, clean production. 4. Its components (wood or other) are preserved with low toxicity preservatives; boards use low or zero emission adhesives. 5. Safe and effective treatments against degradation. 6. Raw material comes from environmentally certified forests. 7. Other components such as fasteners, connectors, joints, adhesives, and isolating materials are evaluated according to similar characteristics.					
	ECONOMICAL	The indicators selected for the economic attribute of product sustainability compliance are: 1. Its production incorporates into the productive chain structure determinations and attributes that add value. 2. Durability improvement 3. Includes recycling 4. Consider renewable and ecologically acceptable resources					
	SOCIAL	The indicators selected 1. It contributes to generate employment (quality work development) 2. Complies with labor regulations 3. Its use and commercialization do not generate social conflicts (Sustainable Forest Management that applies to forest owners). 4. Customers have technical support, after-sales service, component integration alternatives that increase comfort, etc.					
QUALITY	RANKING	The indicators selected 1. The product has labeling or equivalent that guarantees having undergone a technical inspection process of regulatory compliance, classification of its characteristics and properties 2. Its degree of classification corresponds to the relevant for use 3. When classifying it is possible to verify compliance with dimensional requirements, moisture content, type and number of permissible defects					

Table 6. *Cont.*

Category C: Products: from materials or individual construction elements considered raw materials to be transformed into construction elements by themselves or as part of more complex structures such as prefabricated modules and/or homes: Eg Structural/Non-Structural Wood, boards of different types to prefabricated houses.							
Regulatory Compliance with Sustainable and Quality Elements	**Evaluated Atribute**	**DESCRIPTION**	**Scale**				
			1	**2**	**3**	**4**	**5**
PRICE	COST–BENEFIT RELATION PRICE QUALITY RATIO	The indicators selected 1. Price quality ratio indicators: 2. They must be specified with their respective technical data sheets 3. They allow the value differentiation between seemingly equal products, but with different properties					

4. Discussion

The market urgently needs to acquire wooden housing based on attributes and indicators that are effectively evaluated, verifiable and that maintain their continuity over time. These attributes should be expressed in the production sequence of the sector, starting with the requirements, continuing with the approval of the projects and finally the acceptance of the finished work. Even though the market needs regulation and supervision, it cannot be ruled out that the latter should be subjected to verification over time, since it has shown by experience that the home and its surroundings frequently are altered, extended and modified according to the owners. If the municipal-level inspection departments were staffed, trained, and financed, modifications after the final acceptance of the works could be verified and controlled. In the past, this required a high cost of personnel, transport, and visual inspection. Nowadays, the use of affordable technology, such as drones with cameras, makes it unnecessary to utilize high-cost technologies, as satellite images, for instance.

It seems logical to promote these measures to be incorporated by the General Ordinance of Urban Planning and Construction (OGUC) or even by the General Law of Urban Planning and Construction (LGUC) in Chile to become a construction requirement.

Moreover, the sustainability of wooden housebuilding is limited by the consumers' low awareness of its advantages. The stakeholders' point of view about sustainability in these matters is created based on dropping prices of wooden products, wooden structures, and materials. Therefore, the assessment developed through this study will reveal the real stakeholders' perceptions once it can be applied to a wide range of companies. Further research will bring the results based on Chilean prefabricated wooden housing.

Consequently, the latter raises the need for Chile to adopt the obligation for construction inspectors to evaluate housing to issue authorizations and the final acceptance. In this way, end-users will have a better understanding of what they buy, contributing to their own wellbeing and safety, while making neighborhoods in peri-urban areas or the urban–rural interface more sustainable.

Currently, these demands and inspections are requirements that the State eventually demands of the projects and works that are of its interest and responsibility, but which leave out the areas of smaller-scale private projects, such as those that were the subject of this present document.

As can be seen, the implementation of initiatives such as the one proposed in this study must still face important changes and regulatory updates that may still face no minor political resistance.

5. Conclusions

This study offers a first approach to an evaluation of prefabricated housing that considers technical criteria of quality, sustainability, and benchmarking to face more competitive markets.

The selection of indicators and scales allows us to approximate a classification that discriminates between the products offered in the market, including the gaps identified by SMEs.

The evaluation seeks to ensure that suppliers and buyers expand their expectations and aspirations for the commercialization and acquisition of an important asset as a home.

Although there are sustainable building codes, they are voluntary, and the same happens with the housing certification evaluation instrument, which follows global trends regarding the criteria that are evaluated (health and well-being, energy, water, materials and waste, environmental impact, immediate environment). Moreover, the gaps continue to grow, and these instruments do not impact, or do so to a limited extent, the wood construction sector, due to the high disaggregation of construction typologies and business models. Therefore, through the proposed instrument, the stakeholder will identify the key attributes. The suppliers will have the information to improve and foresee relevant aspects before manufacturing wooden housing or wood products and the buyers will find wooden products that fulfill their requirements. Moreover, we anticipate that this instrument will promote that the manufactures will acquire standards to be competitive in the market, thus the customers will have access to high-quality wooden housing at competitive prices.

The government in Chile is moving towards establishing public policies to ensure that the construction market adopts sustainability criteria, instruments such as energy rating of homes, certification of sustainable buildings, and lately, a certification of sustainable housing (CVS) is being created, for which a registry of evaluators and a registry of projects that qualify for this voluntary certification are opened. Consequently, the wood construction sector needs to connect by incorporating differentiating indicators of its sustainability attributes, such as the proposal presented in this research.

Author Contributions: Conceptualization, R.G. and F.P.; methodology, R.G., M.C. and F.P.; formal analysis, R.G. and M.C.; validation investigation, F.P.; writing—original draft preparation, R.G.; F.P. and C.F.; writing—review and editing, C.F., original draft preparation, R.G. and M.C.; supervision general, R.G.; All authors have read and agreed to the published version of the manuscript.

Funding: We are grateful for the financial support of the Agencia Nacional de Investigación y Desarrollo (ANID), Concurso IdeA I+D (project No. IT16i10003).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The researchers thank CONICTY/ANID Fondef for funding for a subsequent application of this tool.

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

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