forests

Review

Is Cross-Laminated Timber (CLT) a Wood Panel, a Building, or a Construction System? A Systematic Review on Its Functions, Characteristics, Performances, and Applications

Victor De Araujo [1,2], Fabricio Aguiar [1], Pedro Jardim [1], Fernando Mascarenhas [3], Lucas Marini [1], Vinicius Aquino [4], Herisson Santos [5], Tulio Panzera [6], Francisco Lahr [7] and André Christoforo [1,*]

1 Exact Sciences and Technology Center, Federal University of São Carlos (UFSCar), São Carlos 13565-905, Brazil
2 Science and Engineering Institute, São Paulo State University (UNESP), Itapeva 18409-010, Brazil
3 Institute for Sustainability and Innovation in Structural Engineering, University of Coimbra (UC), 3030-788 Coimbra, Portugal
4 School of Engineering, São Paulo State University (UNESP), Ilha Solteira 15385-000, Brazil
5 Campus of Ariquemes, Federal Institute of Education, Science and Technology of Rondônia (IFRO), Ariquemes 76870-000, Brazil
6 Mechanical Engineering Department, Federal University of São João del Rei (UFSJ), São João del Rei 36307-352, Brazil
7 School of Engineering of São Carlos, University of São Paulo, São Carlos 13566-590, Brazil
* Correspondence: christoforoal@yahoo.com.br

Abstract: Cross-laminated timber (CLT) has been widely discussed as a relevant industrialized construction solution. Numerous publications have considered CLT as a structural wood-based panel, but other documents have mentioned it as a building or even a construction system. Many authors address its application in multistory buildings, although single-family houses and lower building applications have become desirable topics as well. Given these gaps, this review study addresses a systematic method to evince the functions of cross-laminated timber in construction. The elucidation and discussion were led by technical and scientific contents through publications present in scientific websites and the Google web search engine. Intricate perceptions about the knowledge and reference of CLT functions were identified. From prospections, it was possible to state that CLT is a timber-forest product created in Europe, whose function acts as a structural composite panel of the engineered wood product category. However, CLT has been mentioned by many publications as a building or a construction system. Suggestions were raised to clarify to all readers with respect to misconceptions, and elucidate the construction systems capable of using it as the main resource. Discussions evinced the characteristics and potentials of this wood product. Even with its increasing application in tall buildings, the commercial application of CLT in low-rise buildings may be boosted by the possibility of large-scale production of industrialized houses.

Keywords: forest products; engineered wood products; industrialized buildings; timber houses

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1. Introduction

Timber is one of the most natural materials for structures, whose uses in construction comprise one of the diverse applications of forest products produced around the world [1,2]. Timber-forest products emerge to build a greener future for sustainable societies.

This demand for the mass appeal of timber as the main building material is aligned with technical system components, business economic factors, and improvement in the construction management to provide long-term sustainability [3]. Timber is being called the new concrete by insightful players due to advances both in engineered products and fabrications that provide tall timber buildings with similar behavior, if not better structural integrity, than traditional buildings erected with steel and concrete [4].

This view is reinforced by Viluma [5], whose perception highlights that wood can be machined in different tolerances, from high to low, whereas the new technologies allow reconstituting and using this raw material in a variety of innovative glued-products, making them ideal for prefabrication.

Among the possibilities of timber-forest products oriented to structural uses, there is a wide range of engineered wood products such as plywood (PW), oriented strand board (OSB), cross-laminated timber (CLT), glued laminated timber (Glulam), laminated veneer lumber (LVL), parallel strand lumber (PSL), oriented strand lumber (OSL), and others [6]. Softwoods and hardwoods from planted forests are becoming increasingly important resources to be converted into structural products for sustainable construction [7]. Thus, timber products have been essential to feed the construction sector. While conifer woods are more popular in the production of structural composites, hardwoods are used to manufacture massive products such as lumber and glued laminated timber.

Prefabricated timber residences have been supported by strong arguments concerning important transitions in directions from building site to plant prefabrication and from the smallest to the largest use of engineered products, which contribute to the safe and predictable structural application of wood in civil construction [8,9]. However, there is still little information about houses produced with cross-laminated timber, which is contained in the topic on modern industrialized buildings and becomes a promising residential market alternative driven by large-scale industrialization. Cross-laminated timber is a hot research topic with respect to prefabricated elements for tall buildings, either commercially or residentially. However, the utilization of this input for single-family houses is rarely discussed in the literature. This solution has been cited as a building, a technique and/or a system due to its structural performance. These statements were analyzed using a complete review engendered by multiple sources and discussions.

Therefore, the focus of this systematic review aims to share information about the functions and features of cross-laminated timber, reinforcing its application for low-rise houses. Thus, this paper aims to provide information and discussion to elucidate aspects as well as clarify functions and applications through construction practices related to this bio-based solution, taking advantage of the growing popularity of timber products in regions with a timber industry in more advanced technological development stages.

2. Materials and Methods

This systematic review was utilized to approach and discuss cross-laminated timber in different aspects. Systematic literature reviews, as cited by Dresche et al. [10], are used to map, understand, critically evaluate, consolidate and aggregate results from primary studies on any research topic.

In a synthesis from Linde and Willich [11], Sampaio and Mancini [12] highlighted that this investigation provides a summary of the evidence related to a strategy of specific intervention, by an application of explicit and systematized research method, critical appreciation, and synthesis of the selected information. This secondary research utilizes much evidence proved by other studies to create knowledge through literature syntheses and diagnostics [13]. This method requires straightforward questions, search strategy definition, establishment of study inclusion and exclusion criteria and, lastly, a careful analysis of the literature under verification [12]. From these cited concepts, this paper considered the synthetic script developed by Sampaio and Mancini [12], and successfully utilized by Almeida and Picchi [13], which includes the steps of question and method definition, search strategy, search and codification, result synthesis and presentation.

From this problem description and systematic review, this methodology procedure was selected to provide representative scientific support about cross-laminated timber. Two main topics were observed in this study, from information collected through this systematic review, including:

- Perceptions that cross-laminated timber has been considered a system or technique of timber construction, or even a wood-based structure or a building;

- Discussions about the residential application of cross-laminated timber, as most of scientific publications have directed its goals towards tall and large buildings.

2.1. Strategy of Document Prospection

This study was based on a representative systematic review to identify and collect information from scientific papers and technical documents available on two main search platforms. This strategy aimed to tackle results of different prospections carried out through Scopus and Web of Science search tools.

These prospections were designed through a funneling process using three levels of subject coverage, being initiated by a generalist scenario, continued on an intermediate condition, and concluded in a more specific scope. An overview of scopes and characteristics was raised for each condition, whose results were compared to comprehend the representativeness and depth of these different literature scenarios at global levels.

2.2. Search and Codification

The most challenging step of systematic research represents the definition of search terms and the formulation of strings for the search process, as suggested by Almeida and Picchi [13]. Thereby, this review research sought to compare three different levels of prospection in two scientific databases and, therefore, identify convenient information to approach and discuss the current literary scenario on cross-laminated timber.

Due to the global objective of this study, the prospects were essentially based on documents published in the English language. It is worth mentioning the existence of studies of technical and scientific natures written in other languages (Japanese, German, Chinese, etc.), but their contents are limited to a smaller portion of the world population.

There were no restrictions regarding the temporal period, which allowed the complete verification of all existing publications on cross-laminated timber. This consideration was based on the innovation of CLT, because Gagnon and Pirvu [14] stated that its prototype was created just over two decades ago.

Three scenarios were raised to comprehend the representativeness of CLT, initiated in a generalist condition about itself, followed by another intermediate condition in order to list the publications about construction based on this solution, and concluding with a refined prospection to identify the buildings aimed at its residential applications. Table 1 presents all conditions and their keywords (strings) used with Boolean operators (AND/OR)—this logical technique is defined by verbal relations.

Table 1. Evaluated scenarios and keywords sought with Boolean operators.

Condition	Strings [1]
Generalist stage	("cross laminated timber" OR "cross-laminated timber")
Intermediate stage	(("cross laminated timber" OR "cross-laminated timber") AND ("construction" OR "building" OR "house" OR "housing" OR "residence" OR "residential"))
Specific stage	(("cross laminated timber" OR "cross-laminated timber") AND ("house" OR "housing" OR "residence" OR "residential")

[1] Strings duly used in three prospections for two databases (Web of Science and Scopus).

Both spellings, with and without a hyphen, were considered in all stages (Table 1). Despite the fact that cross-laminated timber is also globally known by its acronym (CLT), this was not considered in the prospections in order to avoid the consideration of other areas that utilize the same acronym for other purposes.

2.3. Synthesis and Presentation of Prospected Results

After the literature prospection for each scenario (Table 1), the results were transferred to electronic spreadsheets in the Excel program of Microsoft Office 2016 (version 16.0, Microsoft Corporation, Redmond, United States). Bibliometric data were extracted in compatible formats with this software, specifically by the "XLS" and "CSV" extensions in Web of Science and Scopus, respectively. From the metrics obtained in this process, graphs and tables were produced to quantify amounts using native resources of Excel. The databases displayed results according to authorship, type of publication, origin and year of publication, volume of publications per year, and other categories.

Regarding the categories, it is worth mentioning the following considerations:

- Due to numerous authors identified, graphical representations were designed to show only those authors with three or more publications in at least one of databases under consideration;
- For the same reason considered in the previous item, the same method was followed in the designs of graphics for the volumes of countries and conference papers;
- Publications categorized as "conference papers" and "proceeding papers" were considered equivalent, but the same convention was not applied to "conference reviews" due to their more simplified contents.

Bibliometric data were organized in specific spreadsheets for each analyzed category. From a file saved in Microsoft Excel, these contents were loaded into the VOSviewer software (version 1.6.18, Leiden University, Leiden, the Netherlands) to design infographics using respective tools from the correlation of data of prospections.

This information allowed the evaluation of the panorama for three levels: the generalist stage, for publications about cross-laminated timber; the intermediate stage, for construction based on CLT products; and the specific stage, on its residential application.

2.4. Synthesis and Presentation of Discussions

After the literature results stage, documents adhering to the present research objectives were selected from their titles and abstracts using the main keywords for the three conditions under observation (Table 1). The selected publications were read, and the more relevant information and arguments were noted to compose the arguments. In addition, technical codes, technical documents and folders of CLT producers, and some scientific papers (from conferences and journals not included in two databases) were also considered to complete specific concepts and elucidate technical data.

During the reading of the prospected literature, different functions were identified for cross-laminated timber. In the discussion section, the approach was carried out to evidence the function of cross-laminated timber and identify the publications that could potentially lead their readers to some misunderstanding or even some confusion on the shared concepts. An elucidation process was introduced to list potential lapses as well as to emphasize appropriate previously established nomenclatures. From exemplifications, there was an examination to identify the publications that failed and/or succeeded in understanding the function and better use of technical expressions.

3. Results

3.1. Results for Three Different Observations: Generalist, Intermediate and Specific Conditions

A bibliometric analysis will be initially presented to denote the current scenario of this subject in the literature according to three levels of subject coverage (Table 1). From their results, a series of publications was selected to compose the discussion sections.

A hundred documents written in other languages were disregarded in this process, despite dozens of contributions written entirely in German, Japanese and Chinese.

The volume per condition was reduced as the prospection sieve was less generic in keywords (Table 2). Thus, the more refined the level is, the fewer documents are found.

Scopus' scenarios outperformed the Web of Science's scenarios by 162%, 205% and 180% for the generalist, intermediate and specific conditions, respectively (Table 2). The amounts per year are higher in Scopus' database (Figure 1). It was expected, as Pranckutė [15] verified an advantage of Scopus due to the greater volume of indexed journals.

Table 2. Cross-laminated timber and respective functions available in research written in English.

Condition	Scopus	Web of Science
Generalist	2142	1326
Intermediate	1432	700
Specific	277	154

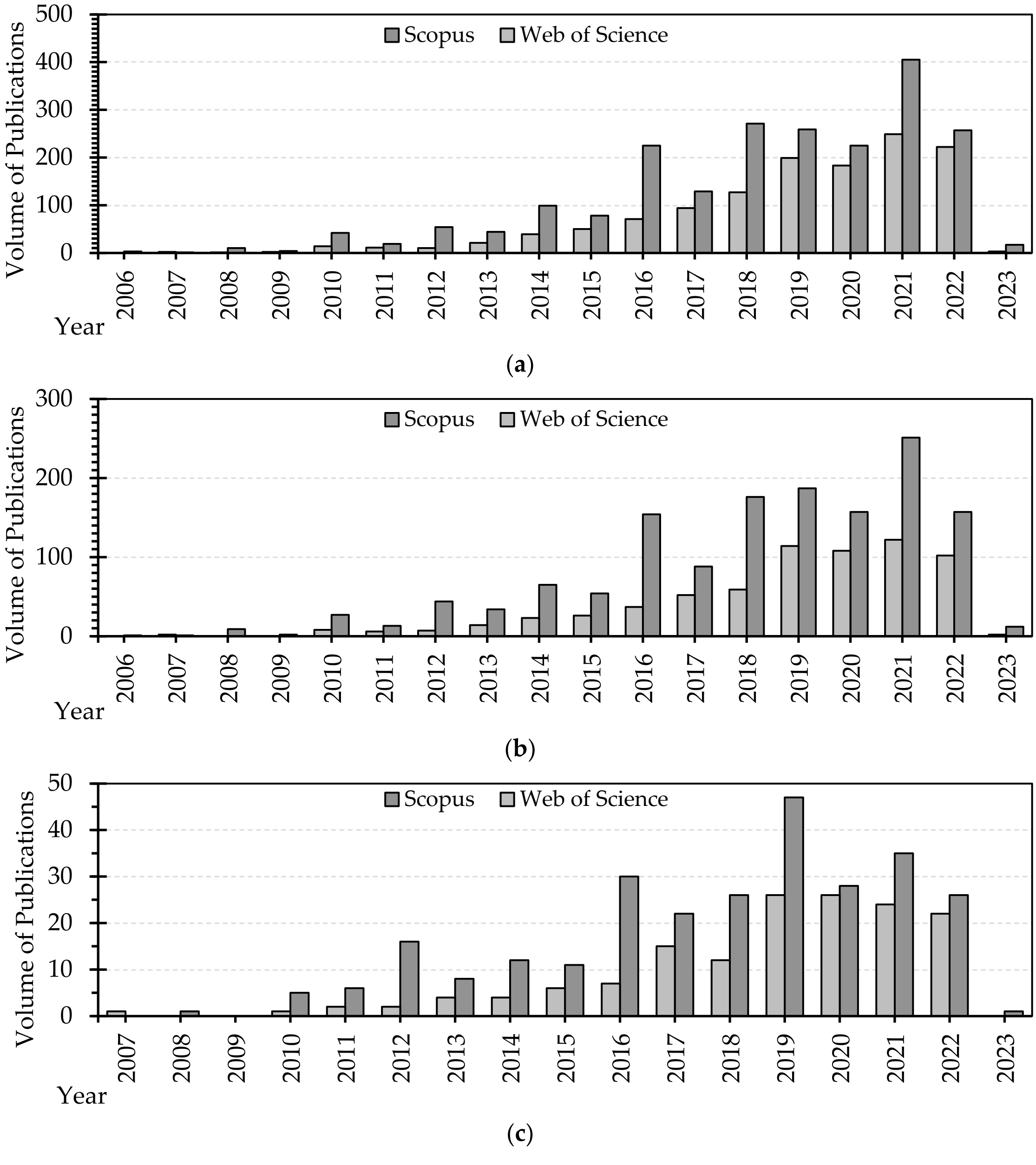


Figure 1. Volume of publications for: (**a**) generalist, (**b**) intermediate, and (**c**) specific scenarios.

Despite some peaks and valleys in some periods, the volumes of publications clearly demonstrate annual growth trends for the three raised conditions (Figure 1a–c). It is also possible to state that cross-laminated timber has shown growing scientific interest over the last ten years. Due to the greater interest in wood product utilization by construction, these scenarios suggest a stable increase in the near future, insofar as some publications were already confirmed for 2023 still during the period of analysis in December 2022.

3.2. Results for the Specific Condition: Cross-Laminated Timber Utilized in Residential Buildings

In the specific condition, over 275 publications are already available in Scopus and over 150 are indexed by the Web of Science database (Table 2). Regarding authorship scope, nineteen authors exceed three or more studies on cross-laminated timber for residential application, the majority of which were presented by professors of Canadian institutions of the British Columbia province: Dr. Thomas Tannert, Dr. Marjan Popovski, and Dr. Cristiano Loss (Figure 2). This consistent presence justified the greater concentration of research studies from Canada (Figure 3). Canadian leadership is followed by the United States, Italy, Sweden, the United Kingdom, and Australia.

Germany, France and Switzerland, where timber culture is traditionally rooted in civil construction, performed below expectations. These and other countries would have performed better if the dozens of publications written in their native languages had been regarded. In contrast, some emerging regions in the timber construction scope are among the main contributors regarding CLT products applied to housing, including Slovenia, Brazil, and Taiwan.

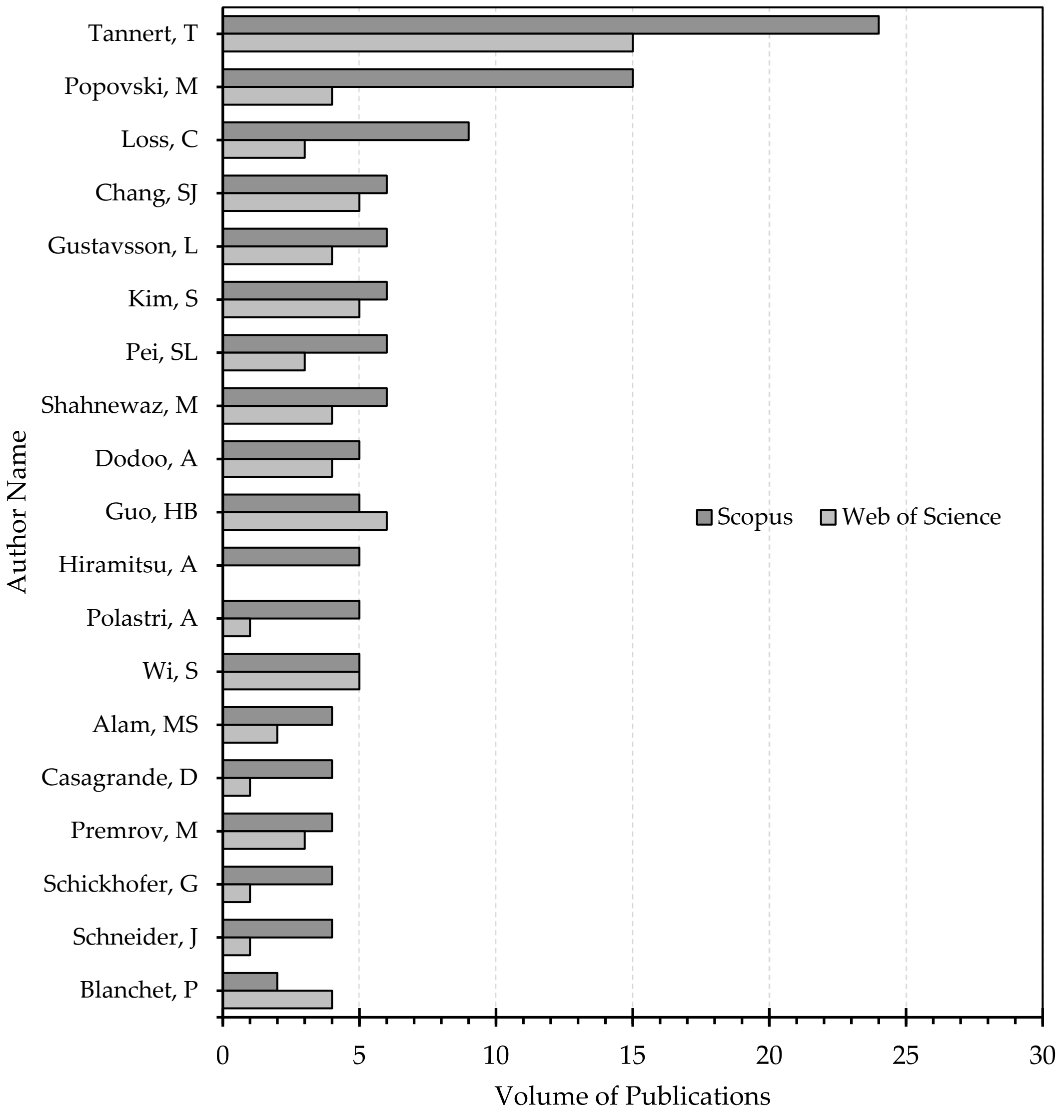


Figure 2. Volume of publications of leading authors in the specific condition.

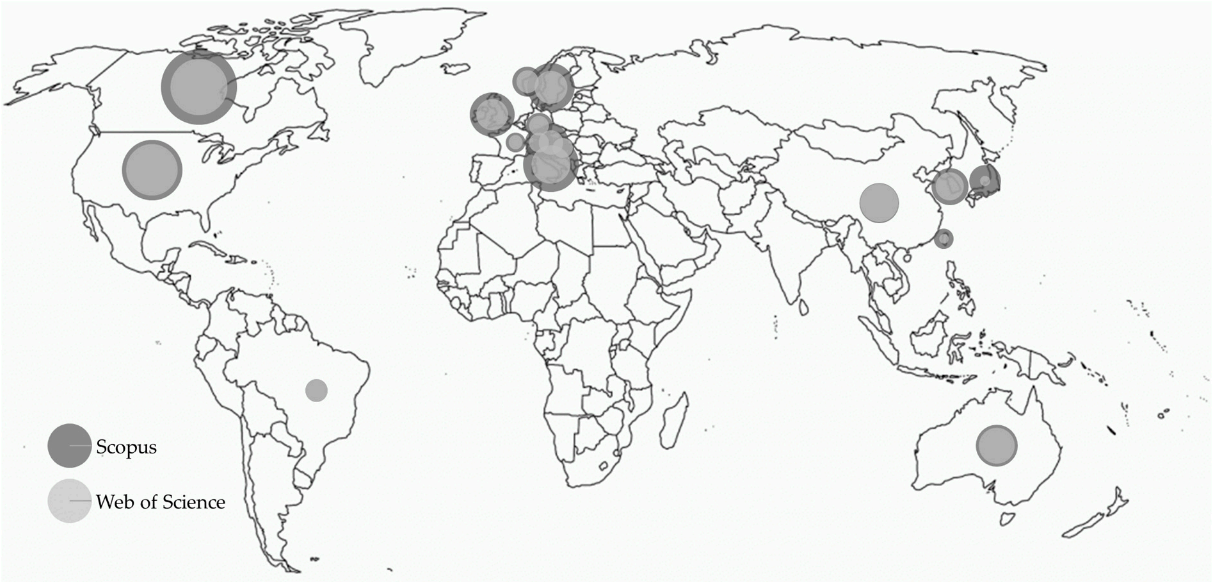


Figure 3. Volume of publications in the specific condition according to origins.

Energy and Buildings, *Sustainability*, and *Construction and Building Materials* are the top three scientific journals with peer-reviewed papers on CLT-based houses. There is a clear predominance of Elsevier, MDPI, and ASCE in these more requested journals (Table 3), although the complete list is extensive and includes journals from other publishers. Buildings, structures, energy, sustainable practices, bio-based products and architecture represent the main topics addressed by the journal titles. Despite the few publications found on the specific condition (Table 2), it is possible to predict a global interest in CLT, since journals from different regions and backgrounds are being requested by authors.

Table 3. Publications in the specific condition according to journals indexed by Web of Science.

Scientific Journal	Editorial	ISSN [1]	Paper Amount
Energy and Buildings	Elsevier	0378-7788	9
Sustainability	MDPI	2071-1050	9
Construction and Building Materials	Elsevier	0950-0618	8
Buildings	MDPI	2075-5309	8
Journal of Building Engineering	Elsevier	2352-7102	7
Building and Environment	Elsevier	0360-1323	7
Engineering Structures	Elsevier	0141-0296	6
Journal of Structural Engineering	ASCE	0733-9445	5
Journal of Cleaner Production	Elsevier	0959-6526	4
BioResources	NCSU	1930-2126	4
Bautechnik	Wiley	0340-5044	4
Journal of Architectural Engineering	ASCE	1076-0431	4
Wood & Fiber Science	Allen	0735-6161	3
Energies	MDPI	1996-1073	3
Structural Engineering International	IASBE	1016-8664	3

[1] International Standard Serial Number of publication.

4. Discussions

All discussions are presented with the identification of the cross-laminated timber functions, the explanation of this product and basic definitions, the main raw materials, production, physical–mechanical performances, fire resistances, applications, residential uses and their advantages and obstacles, modularization of residences, and strategies to proliferate modular houses based on cross-laminated timber.

4.1. Is Cross-Laminated Timber a Wood Panel, a Building or a Construction System?

Most technical and scientific documents have correctly attributed cross-laminated timber as an engineered wood product and/or a composite panel. In the context where cross-laminated timber is designated as a panel, a product and a construction element, approaches were developed by Gsell et al. [16], Frangi et al. [17], Milner [6], Vessby et al. [18], van de Kuilen et al. [19], Niemz and Sonderegger [20], Buck et al. [21], Iqbal [22], Vilguts et al. [23], Brandner et al. [24], Jones et al. [25], Marko et al. [26], Bajzecerová [27], Buka-Vaivade et al. [28], Kukk et al. [29], Leijten et al. [30], Winter et al. [31], Zhang et al. [32], ANSI/APA [33], Danielsson and Serrano [34], Jacob et al. [35], Dacre [36], ISO [37], De Araujo [38], Long et al. [39], and many others.

Cross-laminated timber is a prefabricated structural solid product, as defined by the North American code PRG 320 [33], being among the main materials for industrialized mass timber construction according to Lehmann [40], Iqbal [22], De Araujo et al. [41–43], Harte [7], and others. Other relevant arguments are supported by the European technical codes that define timber-based building designs, Eurocode 5 and 8, insofar as they do not specify cross-laminated timber as a construction system or a building. Therefore, this product is a construction material suitable for structural parts production [44,45].

In sequence, fundamental concepts were substantiated to clarify the matter, where:

- Laminates, plywoods, particleboards, and fiberboards represent the main solutions of reconstituted wood, being produced from mechanical or chemical conversion of lignocellulosic materials into solid products, with or without the use of binding resins [46]. Regarding shapes of raw materials applied to different composites, wooden logs are collected in the forests for conversion into lumber, lamina, fiber and particle elements [47]. Any engineered wood product (EWP) results from the union of any of these raw materials by bonding (resins) or fixing (screws, plugs, dowels, etc.) to obtain a stable structural solid timber [6,48];
- From timber products, plant production of timber buildings is possible through prefabrication and modularization. This condition has translated into advantages since Shimbo and Ino [49] remarked that wood allows the plant production and assembly of prefabricated parts. Compared to masonry, prefabrication may save assembly time, provide a cost reduction for whole process, enable intensive use of labor, and require low investment in capital goods [49]. Modular construction is obtained from the prefabrication of elements or parts of structures, usually produced in industry plants, then transported and assembled on-site [50];
- A housing system based on lignocellulosic materials coincides with any building process that integrates, with consistency and balance, sets of structural elements and/or subsystems made with wood, bamboo, natural fibers, and/or engineered composites [41]. From natural or engineered inputs, timber houses are produced under artisanal and industrial construction systems.

Cross-laminated timber is an engineered wood product categorized as a structural panel, which is used in the form of prefabricated parts for buildings. Due to the functions and applications mentioned by numerous papers and technical codes [6,7,16–45] and fundamental concepts raised from distinct authors [6,41,46–50], cross-laminated timber is not a construction, a building, or a house, much less a system, a construction system or a building system. Reading of the studies prospected in the results section confirmed the existence of conflicting functions given by incorrect “alternative definitions” (Table 4).

Table 4. Cross-laminated timber and the functions mentioned by different prospected publications.

Literary Source/Type of Mention	Correct			Possibly Confused				Incorrect		
	CLT Panel	CLT Product	CLT Element	CLT Construction	CLT Building	CLT Structure	CLT House	CLT Construction System	CLT System	CLT Building System
Gagnon and Pirvu [14]	X	X	X	X	X	X	X	X	X	
Wiegand et al. [51]	X		X	X					X	
Mohammad et al. [52]	X	X	X	X	X	X	X	X		X
Evans [53]	X	X	X	X	X	X				X
Mallo and Espinoza [54]	X		X	X	X	X		X	X	X
Jacquier and Girhammar [55]	X		X			X		X		
Espinoza et al. [56]	X	X		X		X				X
Martínez Soriano et al. [57]	X							X	X	
Perret et al. [58]	X			X	X	X				
Saavedra Flores et al. [59]	X					X		X		
Scotta et al. [60]	X			X	X	X				
Edskär and Lidelöw [61]	X		X		X	X				X
Guo et al. [62]	X			X		X		X	X	X
Hadden et al. [63]	X		X					X	X	
Wieruszewski and Mazela [64]	X	X	X	X	X	X			X	
Jeleč et al. [65]	X	X	X			X				
Quesada et al. [66]	X	X	X		X	X		X	X	
Schmidt et al. [67]	X				X	X			X	
Shahnewaz et al. [68]	X		X						X	
Su [69]	X	X	X	X	X	X				
Berg et al. [70]	X		X			X			X	X
Bermek et al. [71]	X		X		X					X
Cho et al. [72]	X			X	X	X		X		X
Sato et al. [73]	X			X	X	X		X		X
Di Bella and Mitrovic [74]	X		X	X	X	X		X	X	X
Huang et al. [75]	X				X				X	
Wiesner et al. [76]		X			X				X	
Almeida and Moura [77]	X			X		X		X	X	
Nero et al. [78]	X	X							X	
Younes and Dodoo [79]	X		X	X	X					X

Due to this complex situation, accurate and inaccurate designations were searched using the find box of the Acrobat Reader (version 22.001, Adobe, San José, United States). In this literature evaluation, shown in Table 4, "panel", "product", and "element" terms together with both full designations (cross-laminated timber and cross laminated timber) and the respective acronym (CLT) were identified as correct mentions, considering that they were mentions defined by technical codes and scientific papers [6,7,16–45]. The use of this acronym and the full designation with other technical terms could potentially confuse different readers, such as non-native English readers, new professionals and academics, and other people without experience in this matter.

For example, these readers may not fully understand the effective function of a CLT, especially when this product is referred to along with its solution (e.g., building, house, construction, or structure), creating "alternative terms".

Moreover, this misunderstanding may be even more evident and flawed when the full nomenclature and its respective acronym (i.e., cross-laminated timber and CLT) are described together with the working method (e.g., construction system, building system, system, technique or typology) of the building works. In practice, this situation may lead to incorrect mentions, because the designation of any working method fundamentally requires the specification of its construction process or form of production instead of its prevailing material.

From the evaluation in Table 4, it was possible to confirm that all studies mentioned at least one correct term, although they also mentioned one or more inaccurate mentions. Even sharing discussion and information relevant to Science, these studies set a complex precedent for the use of "alternative terms", which might further confuse readers.

The function of cross-laminated timber is clearly addressed by other distinct authors prospected in the results section essentially as an engineered wood product (Table 5).

Table 5. Cross-laminated timber and respective functions mentioned in the literature.

Literary Source	Function
Frangi et al. [17]	Large solid panels used in prefabricated construction systems for bearing wall and floor assemblies
Guttmann [80]	Orthogonal-oriented multi-layer flat solid wood panel to act as structural load bearing elements for construction
Thiel and Schickhofer [81]	Multi-layer structural plate using layers with alternating orthogonal orientation of neighboring board layer
van de Kuilen et al. [19]	Lightweight product formed by crosswise glued layers of timber boards at a high level of industry prefabrication
Herzog et al. [82]	Structural panels made from plies glued orthogonally according to the grain of adjacent plies
Brandner et al. [24]	Quasi-rigid structural panel with an uneven number of transverse layers formed by boards placed side-by-side
Reynolds et al. [83]	Panelized mass timber structural product made from lumber, laid-up in layers, with each layer at right angle
ANSI/APA [33] and ISO [37]	Prefabricated engineered wood product from orthogonal layers of graded lumber glued with structural adhesive
CEN [84]	Structural material of solid timber composed by at least three face-bonded layers, orthogonally oriented
Abed et al. [85]	Panel manufactured in odd number of glued and pressed layers in variable dimensions for floors, walls, and roofs

As an assertive solution to avoid any inappropriate designation of cross-laminated timber in any different functions than an engineered wood product, structural composite lumber, structural wood panel, reconstituted solid timber and/or structural mass timber, it is recommended for future publications to specify the construction system or typology under investigation, analysis and/or discussion. Therefore, the term standardization and correct use of designations in line with the Architecture and Civil Engineering languages are necessary methods to establish an appropriately unified language, especially due to the existence of technical terms for each purpose and function.

The construction application takes place in different manners with cross-laminated timber. A modular house is an example of contemporary timber housing, identified by De Araujo et al. [41], whose construction system can be made from prefabrication of panels, components or volumes, as exemplified by Pique Del Pozo [86].

Therefore, in the context of engineering in the timber industry, buildings based on cross-laminated timber shall be obtained from the following construction systems:

- Artisanal model: compact two-dimensional elements and three-dimensional modules fully produced and assembled on the building site;
- Prefabricated model: two-dimensional elements, from small to large dimensions, produced under off-site conditions in industry plants and assembled with on-site conditions;
- Modular model: three-dimensional modules, from small to large volumes, fully produced and assembled under off-site conditions in industry plants, using advanced industrialization practices (e.g., robotics, automation, etc.).

As a result, there are practical suggestions to restore a single language with respect to "structures", "buildings", "houses" or "systems" made with cross-laminated timber "panels", "products" or even "elements". As a general rule, these terms (e.g., building, house, structure, construction system, building system, system, etc.) shall be specified together with some expressions (e.g., based on, produced with, made with, manufactured with, prefabricated from, industrialized from, etc.) to describe its character and purpose relating to that solution (CLT panel/product/element). As an additional recommendation, future publications shall specify the type of construction system in the production and assembly, in order to better detail the construction technologies and typologies in use.

The following sub-items will address topics on the characterization and application of this engineered wood product as a modern construction input.

4.2. Presenting Cross-Laminated Timber as an Engineered Wood Product

Despite the definition of functions presented in Table 5, more details will be explained. Cross-laminated timber is a timber-forest product as verified by De Araujo et al. [87]. Briefly, Wiegand et al. [51] defined that cross-laminated timber is a laminated, solid wood product applied to loadbearing applications. Historically, this product was created and developed in the Austrian and German regions, and it has been gaining popularity for residential, commercial and infrastructural uses [14], including mixed buildings and greater building heights [88].

In practice, semi-finished products are obtained from artisanal or prefabrication productions, while finished products are manufactured through industry plants with advanced prefabrication and modular processes. Figure 4 exhibits a five-layer CLT panel.

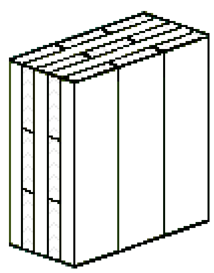
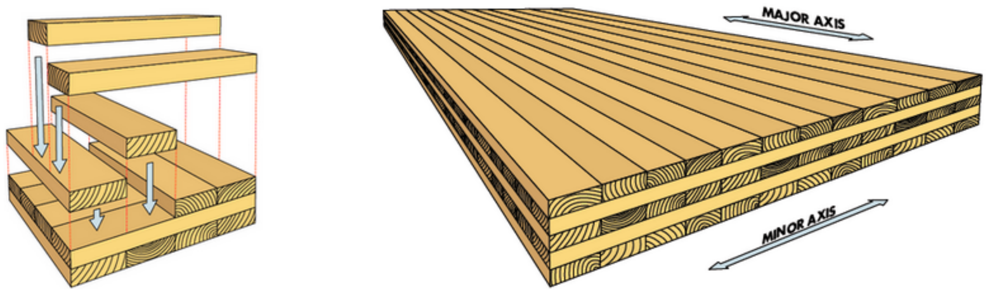


Figure 4. Prefabricated cross-laminated timber panel. Source: drawn by first author.

Cross-laminated timber can be recognized by different acronyms, either crosslam, X-lam or even CLT—its more popular abbreviation. In German, this product is named "*brettsperrholz*", whose acronym is BSP. In Brazilian Portuguese, it is referred as MLCC, whose term is derived from its full nomenclature, "*madeira lamelada colada cruzada*". In contrast, Morgado and Pedro [89] defined that this panel is known in Portugal as "*painel de lamelas cruzadas*". Nomenclatures of this product in other languages include: "*madeira contralaminada*" in Spanish [90], "*legno lamellare incrociato*" in Italian [91], "*bois lamellé-croisé*" in French [92], and "*korslimmat trä*" in Swedish [93].

4.3. Production of a Cross-Laminated Timber Panel

Cross-laminated timber can be manufactured through different technological levels, which include from more artisanal production for a limited number of products to partial or full prefabrication through industry plants and larger production scales. According to Brandner et al. [24], solid sawn timber is individually placed side-by-side and also by overlapping an uneven number of layers (usually from three to seven layers) arranged crosswise to each other at 90°. Figure 5 identifies the panel assembly and axis directions.



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

Figure 5. Cross-laminated timber panel: (**a**) layup and (**b**) axis directions. Source: adapted from Breneman [94].

A new configuration of layers at 45° was experimentally evaluated, which reached a greater bending strength [21]. This configuration presents some complexity with regard to the assembly of layers, insofar as this process generates residues from the exceeded edges. More studies are needed to confirm this performance in line with potential uses of this waste in other panels through a sustainable proposal driven by an integrated chain.

In addition, there is a new concept of cross-laminated timber in the form of a ribbed product, whose reinforced panel is directed to floors and roofs with longer spans in robust and/or multi-story buildings [95,96].

Regarding cross-laminated timber production (Figure 6), Gagnon and Pirvu [14], Lightwood [97] and Kurzinski et al. [98] specified that a typical manufacturing requires:

- Log: logging, peeling, and transport to industry;
- Lumber: planing, selection, defect cutting, grouping, testing, and finger-joining;
- Panel: gluing, layup, assembly pressing, quality control, sanding, and sizing;
- Final product: conditioning, drilling, finishing, marking, packaging, and shipping.

In this process (Figure 6), lumber quality and controlling of the product quality and gluing parameters are key factors for successful manufacture of cross-laminated timber, as cited by Gagnon and Pirvu [14]. A higher level of element pre-processing for modular buildings may be industrially supported by computer numeric control machinery (CNC), which cuts the contours of doors, windows, outlet boxes, holes for valves and taps, and other orifices [20]. Using corporate synergies, the residues of these processing activities could be (re)used in different solutions, developing other timber-based subsectors.

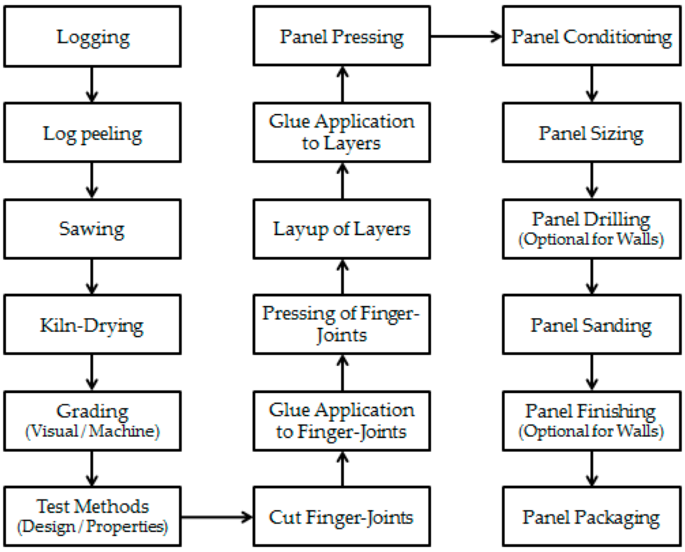


Figure 6. Cross-laminated timber manufacture and stages. Source: drawn by first author.

4.4. Raw-Materials of Cross-Laminated Timber

Timber engineering enables robust solutions, among which cross-laminated timber is referred to as a product formed by the industrialization of laminated layers from solid graded lumber, which is often glued by resins or, rarely, fixed by plugs, screws or pins.

Cross-laminated timber production has prioritized the Gymnosperm species in Europe, which are known for their lower densities [97]. In contrast, some Angiosperm species, with fast-growing properties, are also promising for this purpose [99,100].

Due to the efficient structural performance, Liao et al. [100] and Pereira and Calil Junior [101] also evinced the potential use for "urograndis hybrid" eucalypt (*Eucalyptus urophylla* var. *grandis*). Table 6 lists the commercial wood species used in the production of cross-laminated timber products.

Table 6. Commercial species in use by the global CLT production.

Commercial Name	Scientific Name	Manufacturer	Source
Norway spruce	*Picea abies*	Mayr-Melnhof Holz	[97,102]
White fir/Silver fir	*Abies alba*	SBR	[97,103]
Scots pine/Baltic pine	*Pinus sylvestris*	European producers [1]	[97]
European larch	*Larix decidua*	SBR	[97,103]
Swiss pine/Arolla pine	*Pinus cembra*	SBR and KLH	[103,104]
Douglas fir/Oregon pine	*Pseudotsuga menziesii*	SBR and KLH	[103,104]
Loblolly pine/Bull pine	*Pinus taeda*	Crosslam	[99]
Rose gum/Flooded gum	*Eucalyptus grandis*	Crosslam	[99]

[1] Custom product produced on demand according to requests and wood availability.

As a strategy to preclude pest and fungal attacks, individual boards are kiln-dried to a moisture content of 12 ± 3% [94,105], being eventually lower for some conditions. Thus, this special attention with material drying, combined with standardized cutting and surface smoothing, ensures good levels of wetting and penetration of the adhesive [106].

Different structural adhesives have been utilized in the gluing of laminated layers of wood. Mayr-Melnhof Holz [102] and Gagnon and Pirvu [14] emphasized that the more frequent use of resins includes chemicals based on melamine–urea–formaldehyde (MUF), emulsion polymer isocyanate (EPI), phenol–resorcinol formaldehyde (PRF), and one-component polyurethane (PUR). Polyurethane resins may offer a better adhesion [107]. Due to sustainability issues, Munis et al. [108] and Barreto et al. [109] have suggested the use of castor-oil-based polyurethane resins. Future studies could evaluate the lignin-based resins to obtain a greener panel and, therefore, a more sustainable product.

4.5. Codes and Recommendations for Cross-Laminated Timber

The establishment of safe and stable mass timber buildings using cross-laminated timber shall require a sequencing of some prerequisites suggested by Brandner et al. [24], which are listed in Table 7.

Table 7. Sequencing of prerequisites to build any building using cross-laminated timber products.

Order	Prerequisite Function
1st	Standards and technical documents of products, tests to assess performances, and design of the final application
2nd	Loadbearing models to estimate strength properties of CLT products using values prescribed by standards to value local wood species
3rd	Development of adequate connection systems for economic assembling, and increase the use regarding loadbearing potential of products in their joints

Source: adapted from Brandner et al. [24].

As a general rule, design, production, behavior and properties related to engineered wood products have been regulated by many technical codes. According to Kurzinski et al. [98], this context requires standards and technical codes to ensure the material features in meeting rigorous performance regarding robustness, stability and safety.

Regarding the design and complete project of timber structures, there are several specific codes such as Eurocode 5 [44] from Europe, GB 50,005 [110] from China, NBR 7190 from Brazil [111], and others. There are normative documents that regulate specific conditions, for example, seismic-resistant performances as prescribed by Eurocode 8 [45].

Other specificities can be determined by the type of raw material for construction. Cross-laminated wood, for example, is an engineered wood product that has been treated and regulated by standards and codes from different regions (Table 8).

Table 8. Main technical codes focused on cross-laminated timber products.

Technical Code	Region	Organization	Source
ISO 16696-1	World	ISO	[37]
EN 16351	Europe	CEN	[84]
ANSI/APA PRG 320	North America	ANSI/APA	[33]
SANS 8892	South Africa	SANS	[112]
JAS 3079	Japan	JAS	[113]
NBR 7190 (part 7)	Brazil	ABNT	[111]

There is also the case of Australia and New Zealand, which share a manual for designing structures produced with cross-laminated timber, whose purpose has provided key information on material properties, design principles, connections, and free spans [114]. In general, Kurzinski et al. [98] specified that cross-laminated timber production shall utilize lumber, structurally graded and kiln-dried to a 12 ± 3% moisture content, with typical dimensions up to 51 mm thick and 240 mm wide. However, there is available technology for the prefabrication of panels with dimensions ranging from 4000 to 18,000 mm in length, 1150 to 3500 mm in width, and 51 to 4000 mm in thickness [115].

4.6. Physical and Mechanical Performances of Cross-Laminated Timber Products

In the panel plane, the crosswise arrangement of the longitudinal and transverse laminated layers increases shear capacity and reduces the consequences of swelling and shrinkage, as well as increasing the static load-carrying capacity [19,104]. The mechanical behavior of CLT is complex, especially due to the inherent anisotropy of wood and the orthogonality in relation to the grain direction of consecutive laminated layers [116]. Some studies may observe stresses in the glue line caused by the cyclic action of wind.

Cross-laminated timber panels can create an effective lateral load-resisting system during seismic motion due to the rigidity and stability of this orthogonally laminated panel [117]. This condition may provide better seismic behavior, especially if element connections designed to dissipate energy are used. Therefore, modern interconnection devices shall be designed to provide a safe, stable and resistant mass building. Fixation elements, connections and resources towards energy dissipation are important research fields regarding resistance capacity and seismic-resistant solutions. Positive outcomes in these topics have been confirmed by Latour and Rizzano [118], Scotta et al. [60], Chen et al. [119], Hashemi and Bagheri [120], Fitzgerald et al. [121], and other authors.

The high performance of cross-laminated timber utilized in the production of timber buildings is proved by the good results obtained by different studies on seismic behavior. This potential was evinced by Ceccotti [122], Fragiacomo et al. [123], Gagnon and Pirvu [14], Ceccotti et al. [124], Pei et al. [125,126], Zhang et al. [32], Tannert et al. [127], Yin [117], Sato et al. [73], Shahnewaz et al. [128], and others. An extreme situation was successfully observed by Quenneville and Morris [129], using a seven-story building integrally made with cross-laminated timber, which withstood some severe movements similar to the impact of a 7.2-Richter-scale earthquake.

Physical and mechanical performances are important factors for construction. Table 9 shows the main physical and mechanical properties of CLT panels produced by some of the leading producers. These commercial panels demonstrate similar properties—the only exception occurs in the modulus of elasticity of Stora Enso's panel, whose property and product classification were improved due to the insertion of a cement screed.

Table 9. Main commercial cross-laminated timber panels and physical–mechanical performances.

Producer	D [1]	CS [2]	MOE [3]	TC [4]	SSPL [5]	SSPA [6]	Source
KLH Massivholz	500	–	–	0.12	0.02	0.24	[104]
Stora Enso	500 [7]	–	26,000 [7]	0.12 [7]	–	–	[130]
Hasslacher	480	24.5	14,700	0.12	0.01	0.24	[131]
Binderholz	480	21	12,000	0.12	0.01	0.24	[132]
Mayr-Melnhof Holz	480	24	11,500	0.10	0.01	0.24	[133]

[1] basic density (kg/m^3); [2] compressive strength (N/mm^2); [3] modulus of elasticity (N/mm^2); [4] thermal conductivity (W/m.K); [5] shrinkage-swelling behavior on panel level (%); [6] shrinkage-swelling behavior on perpendicular angle to panel level (%); [7] with cement screed.

Physically, wood is a natural raw material with a hygroscopic capacity that releases and absorbs moisture [133]. This movement of fluids is facilitated by the complex solid and porous structure of wood, allowing drying and impregnation treatments to provide improved capabilities in relation to dimensional stability, decay and fire resistances, and strength properties [46]. Wood preservation and surface finishing restricts this capacity. Climatic conditions of the environment interfere with the equilibrium moisture content of wood products [133]. Later equilibrium in the normal use status is wood-specific, and not easily prevented [130]. Although studies and codes have prescribed the use of kiln-dried lumber at 12 $\pm$ 3% for efficient production, the moisture content of finished products must be adapted to the subsequent installation to avoid dimensional changes [33,98,111,133]. As wood is sensitive to moisture variations, which persist in engineered wood products, shrink–swell capacity is also present in cross-laminated timber (Table 9).

Cracks and open joints are caused by the natural shrinkage and swelling behavior, being dependent on the ambient conditions in which cross-laminated timber is inserted. The prevention of these problems is favored by the stable moisture of the CLT parts of a building, whose process shall prioritize sufficient ventilation and careful heating [133]. The difference of moisture contents between indoor and outdoor conditions can generate moisture gradients, whose effects induce stresses responsible for the failure formation.

Compared to sawn wood, shrinkage and swelling have manifested at lower levels in cross-laminated timber, being practically eliminated in the plane of the panel due to its crosswise layering [19]. This better condition is possible due to the material gluing and crossing of layers, as these facts contribute to the production of a solid element formed by wooden layers of alternating grains. According to the Stora Enso [130], this orthogonal configuration can also prevent the appearance of any convection phenomena.

Moreover, the durability of engineered wood products is also affected by moisture, especially in those parts and elements out of the equilibrium content, insofar as this fact favors fungal decay and pest attack [94,105]. Among timber materials, cross-laminated timber offers the best durability performance, being the most cost-effective option [21].

4.7. Fire Resistance of Cross-Laminated Timber Products

Negative perceptions regarding fire safety in engineered timber-based buildings are among the main barriers to greater architectural aspirations regarding these examples [63]. Thus, fire resistance is a functional and structural concept, being determined by the time that an element supports its functions assigned to a building [134]. The importance of fire safety in buildings made with cross-laminated timber products is frequent in the scientific literature. This topic was observed by Frangi et al. [17], Gagnon and Pirvu [14], Klippel et al. [135], Wong and Tee [136], Lineham et al. [137], Hadden et al. [63], Henek et al. [138], Su [69], Wiesner and Bisby [139], and others. These studies emphasized that cross-laminated timber reaches an excellent level of fire resistance.

According to Wong and Tee [136], the intensity observed in this structural panel is "... comparable to that of non-combustible raw materials and to heavy timber construction, maintaining most of their strength during this fire exposure". According to Table 10, the five main commercial CLT panels were classified as "D-s2, d0" medium combustion products with an average smoke intensity and without flaming droplets.

Table 10. Main commercial cross-laminated timber products and fire performances.

Producer	CR [1]	SC [2]	DC [3]	C [4]	Source
KLH Massivholz	D/medium	s2/average	d0/no drops	–	[104]
Stora Enso	D/medium [5]	s2/average [5]	d0/no drops [5]	0.6–1.3 [5]	[130]
Hasslacher	D/medium	s2/average	d0/no drops	0.6–0.8	[131]
Binderholz	D/medium	s2/average	d0/no drops	0.7–0.9	[132]
Mayr-Melnhof Holz	D/medium	s2/average	d0/no drops	0.6–0.9	[133]

[1] class of reaction; [2] smoke class; [3] drop class; [4] charring (mm/min); [5] with cement screed.

4.8. Sustainability of Cross-Laminated Timber Products

If more forests are sustainably harvested to be converted into timber buildings, an increase in forest area of just a few percent will be needed and, consequently, carbon from this wood will be effectively sequestered as construction parts [2]. Planted forests provide a notable ecological potential, establishing a sustainable modern society by the consumption of products from renewable bioresources [140]. Timber forest products have been developed to replace unsustainable solutions, especially those based on non-renewable resources, whose change is reinforced by versatile uses and high industrialization levels [87]. The carbon is preserved in wood when it is used as construction material, which provides long-term carbon fixation [141]. Table 11 reinforces the climate benefits of wood- and bamboo-based products, which were classified by Carcassi et al. [142] according to their climate influences. Replacing non-renewable materials with renewable options may be justified by their lower carbon emissions and even negative levels. Even engineered products manufactured by reconstituting bioresources in glued composites for structures have become environmentally advantageous options compared to non-renewable options (Table 11).

This use of engineered products offers environmentally positive attributes, whereas it provides greater material rationalization, water-free processing, work site cleaning and, above all, a faster construction process due to prefab solutions [42].

Table 11. Diet of main construction materials.

Climate Influence	Construction Material Type	Type of Source	Net-Global Warming Potential (kg CO_{2eq}/kg)
High-carbon	Insulated triple glazing	Non-renewable	99.89
	Plastic window frame	Non-renewable	8.77
	Wood window frame	Partially renewable	4.18
	Polyethylene membrane	Non-renewable	2.70
	Steel	Non-renewable	2.22
Low-carbon	Mineral plaster	Non-renewable	1.07
	Solid softwood lumber	Renewable	1.05
	Ceramic tiles	Non-renewable	0.87
	Bamboo flooring	Renewable	0.77
	Gypsum plasterboard	Non-renewable	0.39
	Cross-laminated timber	Renewable	0.31
	Glued-laminated timber	Renewable	0.31
	Oriented strand board	Renewable	0.29
	Concrete C30/37	Non-renewable	0.18
	Concrete 25/30	Non-renewable	0.16
	Concrete deep foundation	Non-renewable	0.14
	Clay plaster	Non-renewable	0.09
Negative carbon	Solid hardwood lumber	Renewable	−0.14
	Glued-laminated bamboo	Renewable	−0.15
	Cross-laminated bamboo	Renewable	−0.16
	Hemp fiber	Renewable	−0.44
	Reed mat	Renewable	−0.46
	Straw	Renewable	−0.60

Source: adapted from Carcassi et al. [142].

The natural properties of wood offer an advantage in the construction industry as they enable structures to be designed and built that remain sustainable and operational [130]. The use of cross-laminated timber reduces around 40% of the carbon footprint when they are directly compared to conventional construction materials, steel and concrete, widely consumed by construction [79]. However, it is possible to reduce the impacts by efficient choice of woods and fasteners [143].

Despite the good performance of some concrete solutions, classified as low carbon (Table 11), the production of construction elements still requires water for mortars and, in most cases, steel for reinforced elements.

4.9. Applications of Cross-Laminated Timber Products

Due to multiple advantages, Abed et al. [85] emphasized that mass timber can present a high performance as the material of the future, both for its low-carbon attributes and benefits of competitive costs and efficient structural features to be considered in tall buildings, especially due to effects against fire, wind and earthquakes. This strength is identified by Amorim et al. [116], whereas cross-laminated timber behaves as a rigid element using a variable layer configuration for sealing and structural functions.

The orthogonal, laminar structure of a cross-laminated timber product allows its application as a full-size wall and floor element as well as a linear timber member, able to bear loads in- and out-of-plane [24]. The resulting alternating grain directions give CLT strength and stiffness in two directions, making this panel suitable for two-way spanning slabs, walls, and diaphragms [137].

Cross-laminated timber can be applied to multi-story buildings, bridge structures, and prefabricated buildings [116]. Long-span structures can be made from rib floors or box girders together with linear and planar products of cross-laminated timber and the addition of other engineered wood products [24]. The easy combination of CLT products with other engineered wood products (Glulam, LVL, LSL, OSL, PSL, etc.) and metal parts evince its versatility for construction.

Multi-story buildings made with cross-laminated timber panels are becoming an economically valid alternative in Europe compared to traditional masonry or concrete buildings [124]. Up to 10 floors, the primary panelized structure has been prioritized together with the use of prefabricated parts and elements based on cross-laminated timber [144]. Thus, the popularization of CLT in the production of low-rise buildings and houses are possible, as this solution is able to satisfy different conditions.

In this sense, Mayr-Melnhof Holz [102] described that cross-laminated timber products may be efficiently used, under prefabricated and modular systems, to produce:

- Single and multi-family housing;
- Multi-story residential housing (condominiums);
- Kindergartens and schools;
- Commercial and administrative buildings;
- Hospitals and clinics;
- Industrial buildings;
- Agricultural buildings;
- Addition of new built stories;
- Urban aggregation and infrastructures;
- Tourism and leisure-time infrastructures.

4.10. Residences Made with Cross-Laminated Timber Products

Cross-laminated timber products present a strong correlation with larger and taller buildings. This is confirmed by approaches regarding multi-story buildings based on CLT. The publications include Quenneville and Morris [129], Ceccotti [122], Chapman [145,146], Fragiacomo et al. [123], van de Kuilen et al. [19], Ceccotti et al. [124], Abrahamsen and Malo [147], Dunbar et al. [148], Hindman [149], Zhang et al. [32], Ramage et al. [144], Vassallo et al. [150], Yin [117], Connolly et al. [151], and others.

Under a low-carbon view, modular construction may be utilized to build residential infill development of 10 stories or higher as suggested by Lehmann [40], or even in low-rise residences as mentioned by Mayr-Melnhof Holz [102], Villani and Rossini [152], De Araujo et al. [41], Popovski and Gavric [153], Martínez Soriano et al. [57], van de Lindt et al. [154], and Wigo [155]. Additionally, Casagrande et al. [156] developed a hybrid version for emergency housing facilities to use potentials of CLT products, whose result may be favorable to reestablish populations. About a quarter of the modular buildings have been produced using CLT for temporary structures with different purposes [157].

There is a wide potential for cross-laminated timber products—already practiced by some countries—in the production of single-family residences through modular systems. Whether from prefabrication or modularization processes, as suggested by De Araujo et al. [41], a house can be assembled on site from two-dimensional components (floors, walls, and roofs) or three-dimensional modules industrially manufactured.

The choice of construction system depends on the available industrial technologies of cross-laminated timber producers and work conditions and management processes of contractors, including production capacity, manufacturing line, computer-aided design and manufacturing, and advanced machinery (automated machines, robots, etc.). Thus, an efficient combination of production technologies and capacities offers prefabrication, while a full condition allows the modularization of buildings.

4.10.1. Benefits and Obstacles of Houses Made with Cross-Laminated Timber Products

Construction prefabrication and modularization are efficient strategies to produce industrialized houses in large scales, group and manage production stages in covered spaces (e.g., factory, manufacturing plants, etc.), control systematic processes, reduce cost and time, standardize processes and products, and improve and ensure product quality.

These conditions are enabled by wood, whose material is ideal for component and part prefabrication, both for its workability, structural integrity and for similar behavior to traditional materials [4,5]. CLT products utilize the industrialization of sawn wood by intensive processes [82]. Regarding CLT-based buildings, they are becoming more popular due to sustainable advantages, alongside excellent benefits in terms of the production speed and ease of construction for any urban center and very congested area, intense use of offsite construction method driven by prefabrication and modularization, and reduction in foundation size due to lower mass of the building [137].

Design flexibility, cost competitiveness and fire protection are further advantages reported by Evans [53]. The suitability of this material in multi-story buildings for earthquake-prone regions is justified by the self-centering capabilities and high stiffness combined with ductility to avoid brittle failures [124].

Crosswise layering reduces the swelling and shrinkage rates of cross-laminated timber, conferring it a high dimensional stability. In contrast, this product remains vulnerable to moisture, being essential to address peculiarities and treatments [24]. The good performances on structural, fire, and environmental issues are shown by Tables 9–11. Due to high industrialization, the production of a modular building based on CLT has one the most efficient times among timber construction techniques [158].

Another benefit refers to the healthier indoor environment, which presents good acoustic and thermal insulations [20,159]. These mass buildings offer good levels of airtight envelope and wall-vapor permeability, combined with a light weight, greater distribution of loads, wide adaptability to many finishes, and high carbon storage [105]. In contrast, the lack of experience of contractors and professionals with respect to CLT, slow governmental support to adopt this new material in public buildings, and higher costs of this engineered product due to a limited number of local producers represent the main critical barriers, including developed nations such as the United States [126]. A lacks of policies and new investors, corporate partnerships, cultural barriers, and panel supply have been the leading obstacles of timber construction [160].

A residence based on this material can cost, in terms of square meters built, up to four times more than any masonry example [20]. An industrialized house integrally made from cross-laminated timber products, when compared to a house made with artisanal masonry, can exceed the costs by 30% for popular options and exceed 80% in the upper-class examples [161]. Increasing its market consumption may soften this contrast.

In general, some challenges shall be solved by the industry oriented to cross-laminated timber products as listed by Quesada et al. [66], including the market lacking buildings based on this material, lumber production and procurement in the required specifications of sizes and qualities, demand for training on the product manufactures, and architects' and engineers' unfamiliarity about their possible applications. In addition, maintenance and repair plans shall be observed. New studies could address these topics.

4.10.2. Houses Produced by Modular Construction System from CLT Products

In the last two decades, the majority of modular buildings based on cross-laminated timber were produced in Europe, which explains the maturity of the regional markets as evaluated by Bhandari et al. [157]. However, these modular examples are marketed in other countries such as Brazil [162]. In this Brazilian perspective, a modular house fully made with cross-laminated timber presents a cost superior to USD 600 per square meter built, although it may easily exceed USD 1500 in the upper-class options [161]. However, the large-scale production could significantly reduce these costs due to intense operational controlling. This efficient process can be organized by the script in Table 7.

The modularization process of any house takes place primarily in industry plants, whose manufacturing infrastructures include operations such as processing sawn wood into cross-laminated timber, processing and machining of panels, assembling processes (walls and structures, windows and doors, plumbing and electrical installations, further infrastructures, electronic equipment, and finishes) and, finally, packaging and storage.

Outside of the industrial environment, the finished modules are loaded onto robust trucks, transported to the construction site, lifted and positioned in the right location on the ground, merged together through fasteners, and connected to available supplies.

While one-story single-family residences are industrially produced with one or two modules, it is also possible to manufacture a house with two or more stories through a configuration with more volumetric modules, being usually partially finished (Figure 7).

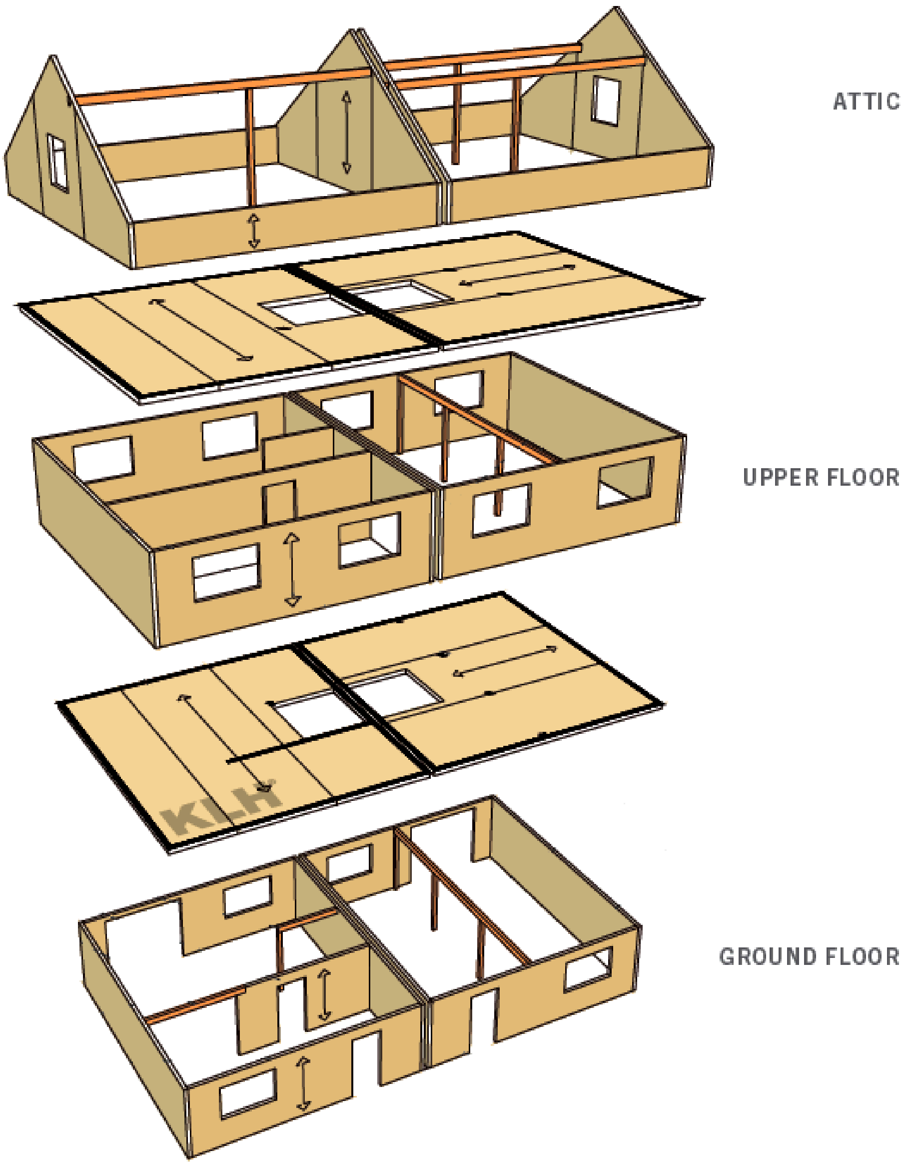


Figure 7. Configuration of modules for a single-family residence. Source: adapted from KLH [163].

The larger and more numerous the modules, the more constraints there will be, especially with transportation charges due to increases in the numbers of journeys and truck vehicles to be used [164]. More compact projects become convenient and economically viable ways to utilize good possibilities and benefits of cross-laminated timber in residential uses.

4.10.3. Strategies to Proliferate Modular Residences Based on Cross-Laminated Timber

Over the last 10 years or so, timber has recaptured market shares from mineral-based solid construction materials lost in previous decades, in particular for residences, offices, and schools but also other fields of construction [24].

The market construction based on cross-laminated timber is visible in Europe and North America, but Brazil and China already have emerging markets for residential and commercial purposes [162,165].

Despite the development of wood utilization in some countries, Koppelhubber et al. [3] determined that more effort is required within the scientific community, not only in the technical sector but more than ever in the construction segments to allow this useful and ecologically friendly material to become widely used in buildings.

Thus, good governance and sustainability of this and other activities based on forest production shall prioritize, according to Birben and Gençay [166], a re-organization of decision-making mechanisms with more participative approaches of the populations, governments, and sectors. In contrast, there is a demand for new housing policies suitable and adapted to the production of greener and more sustainable houses based on the use of wood and its engineered products [167].

In the scope of product availability, the governmental leaders shall stimulate the proliferation of modern construction technologies and productions in order to stimulate the sector industrialization and revert to the market dominance by a limited number of developers [160]. Regarding cross-laminated timber, Quesada et al. [66] proposed that learning from failures, successes, and best practices of leading CLT companies in Western Europe can help support the potential development of this panel manufacturing capacity elsewhere. These authors still suggest that projects of new buildings and remodeling of existing buildings, especially those oriented to public services (health, education, administration, etc.), shall lead this movement as case studies to evince the advantages of mass timber construction. A convenient method could be based on the institution of standardized dialogues through national documents about project design and execution of new housing solutions, as recently led by Jellen [168] in the United States.

Alternatively, there is a quite attractive occasion, both for current producers and for future developers, in the decentralized creation of new manufacturing plants to quickly supply regions dependent on infrastructure.

Inspired by existing temporary housing, new compact projects would add different advantages of cross-laminated timber to the possibility of converting this construction input into prefabricated parts, which are assembled to produce industrialized houses on a large scale. From the development of user-centered projects and leaner and cleaner production practices, these manufacturing plants could satisfy the demands related to expansions of new houses to supply housing deficits and newly formed small families, and also the replacement processes of dwellings to rebuild urban centers affected by environmental disasters and war conflicts. Therefore, the potential use of cross-laminated timber to meet the priorities of our society becomes evident and opportune.

In the face of few studies on modular residences based on cross-laminated timber products (Table 2), this gap could be filled by the research development to promote these options and give the potential of this field compared to less specific studies (Figure 1a,c), especially for social housing and compact housing for families with few people. These proposals may assist in the mitigation of housing deficits for both methods and consolidate efforts to the housing modularization in large scale.

5. Conclusions

From this systematic review, it was possible to compare results from prospection systems of two main scientific databases: Scopus and Web of Science. Over two thousand publications about cross-laminated timber are available in Scopus' database in early 2023, while over a thousand documents are contained in the Web of Science's database.

Using a filtering process in the prospected documents, it was possible to verify that most of them are dedicated to construction scope. Another refinement showed that more than 250 documents of Scopus and 150 of the Web of Science, in one way or another, have addressed residential buildings based on CLT products. The first studies were published in the early 2000s and publications were intensified a decade later, reaching two hundred papers per year; this fact justifies the increasing global interest on this topic.

In the face of the main question that is raised of whether cross-laminated timber could be a wood panel, a building or a construction system, it was possible to verify that most of the literature has correctly attributed its main function as a wood-based panel, or even an engineered wood product, for structural uses in construction. Despite some triviality, different mentions were still confirmed, which could lead to a dubiety or misconception of the purposes of this product, both for new professionals and readers.

Although many publications have correctly identified that cross-laminated timber is a panel, a product and a structural element, prospections identified that CLT has been designated as a building, a structure or a house in some confusing references. These mentions are not incorrect, but they need further definitions. Three wrong mentions were identified about this product, referring to it as a system, either a building system or a construction system. This failure becomes more evident when some publications do not clarify that CLT is a timber forest product, also classified as an engineered wood product, processed into structural elements for industrialized buildings built through different construction systems, which include prefabrication of two-dimensional elements (walls, roofs, floors, and other parts) and modularization of three-dimensional volumes (partial, semi-finished and finished modules). In response, suggestions were presented to eliminate this gap and clarify that a building, a house, a construction system, a structure, and a system are "based on", "made with", "produced with", "manufactured with", "industrialized from" or "prefabricated from" this engineered wood panel. Thus, the utilization of correct mentions may ensure a greater assertiveness of what is being designated or cited.

At least eight wood species and four types of structural resins are commercially used by the timber industry. High levels of structural integrity and strength, intense use of biomaterials from highly renewable sources, high carbon fixation, and very efficient part prefabrication are positive attributes of this lightweight massive product. The structural purpose of this product meets different rigorous standards of resistance to earthquakes and fires, making it suitable for multiple applications, including residential, commercial, industrial, infrastructural and agricultural uses. Due to the diversification of applications and technical advantages in the structural, environmental and industrial contexts, a growing interest on the cross-laminated timber is emerging worldwide, whose engineered products have been valued for the production of robust and tall buildings. These modern buildings are manufactured in high-technology production plants capable of producing different prefabricated structural elements and even finished volumetric modules under large scales.

Hence, there is a great market opportunity for this global production to be rethought and therefore expanded in order to offer economically viable standardized residences produced on a large scale using diversified or standardized projects from customized solutions of modular housing for different markets and demands. In the academic field, different approaches are still needed to provide knowledge about cross-laminated timber products, including investigations on the development of low-cost industry processes, design of compact social housing solutions using accessible industrialization processes, evaluation of conditions and features of the current developers, analyses on the product performance about durability and protection using different resources and requirements (strength, fire, moisture, decay, etc.), life cycle analyses dedicated to sustainably developing the industrial processes, (re)design of commercial cross-laminated timber using greener inputs (bio-based resins, biochemical preservatives, certified woods, etc.), and policies to formally consider this sustainable product as a convenient option for housing expansion.

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