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Systematic Review

Scientometric Analysis for Cross-Laminated Timber in the Context of Construction 4.0

Emanuel Martinez Villanueva, Jennifer Alejandra Cardenas Castañeda and Rafiq Ahmad *

Laboratory of Intelligent Manufacturing, Design and Automation, Department of Mechanical Engineering, University of Alberta, 9211 116 Street, NW, Edmonton, AB T6G1H9, Canada
* Correspondence: rafiq.ahmad@ualberta.ca

Abstract: Cross-laminated timber (CLT) has been one of the principal materials in mass timber construction, and now it is possible to find mid-rise and high-rise projects around the globe. This study makes a scientometric review comparison between CLT and the impact of the fourth industrial revolution (formally known as Industry 4.0) in the construction industry, focusing on worldwide academic publications between 2006 and 2022. The analysis considers keywords, co-author, co-citation, and clustering analysis. This study used 1320 documents, including journals and conference proceedings from the Scopus database, where 753 were for cross-laminated timber and 567 for Industry 4.0. Key researchers, research institutions, journals, publications, citation patterns, and trends are some of the results obtained from the scientometric analysis. Once the knowledge mapping was conducted for both fields, scrutiny of the interconnection of both areas was performed to find possible research gaps from a manufacturing perspective. Among the conclusions, it is logical to say that Industry 4.0 implementation in cross-laminated timber is still in its infancy. One of the most popular technologies impacting construction is the digital twin concept; however, no work is reported for CLT on this topic. Additionally, digital automation is a necessity in any research practice, and the use of industrial robots is shown to be an essential asset for CLT as these robots can handle complex shapes.

Keywords: cross-laminated timber; CLT; Construction 4.0; critical review; scientometric analysis; off-site construction

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1. Introduction

Mass timber is a wood-based solution for the construction industry in its pursuit of sustainability, and cross-laminated timber (CLT) is one of the most common materials used within this type of construction [1,2]. The construction industry is responsible for using multiple global resources, 40% of the energy, 25% of water consumption, and close to 30% of the global greenhouse gas emissions (GHG) [3]. Thus, there is a need for this thriving awareness to develop renewable materials that reduce resource depletion and help with multiple environmental concerns. Timber, a cellulose-based material, is commonly used for this renewable alternative. The first appearance of CLT was in Europe in the 1990s, and it had different names in its development, such as "x-lam" or "cross-timber" [4,5]. Since then, the industry has considered CLT one of the best sustainable materials, and it has been an exciting topic for researchers. One example of the current work is the study from Nordin et al., whose work was dedicated to manufacturing CLT panels with tropical hardwood for better commercialization [6]. Another instance is the intelligent methodology [7] to optimize the CLT panels required in buildings, removing material that is not needed or reinforcing them with higher performance requirements [7]. Yet, there are still many developing areas for cross-laminated timber, and this study explores these prospective opportunities.

On the other hand, Industry 4.0 is the transformation of manufacturing processes where multiple technologies are integrated within a production environment, characterized by its high virtual, digital, and technological performance [8]. This revolution has mainly taken place in the manufacturing sector; however, the construction industry is starting to take features from the new technology to improve performance and reduce cost [9]. The new paradigm that bounds these two fields is referred to as Construction 4.0, which focuses on digitalizing the construction processes [10]. One example of the progress is the work of Webster [11], who uses artificial intelligence (AI) to route and harness wires and cable layouts in building construction [11]. On the other hand, we have the work of Kim et al. [12], who created a vision-based hazard avoidance system with the help of augmented reality and informed the workers of potentially hazardous situations [12]. Nevertheless, this study will delve into the progress Industry 4.0 has made with cross-laminated Timber (CLT), aiming to find possible areas of opportunity.

A comprehensive study of CLT manufacturing and Industry 4.0 is still missing in the literature. Therefore, this study will highlight the important developments in this field using the "scientometrics approach", which is defined as those quantitative methods that deal with the analysis of science viewed as an information process [13]. Scientometrics has already been used in other journals in construction-related reviews on topics such as computer vision [14] and building information modeling (BIM) [15]. Nevertheless, the difference in this article is the comparison between two construction-related fields. This study intends to analyze the current state of both fields, CLT and Industry 4.0, in construction so it is possible to identify the research gap from a manufacturing perspective. It is worth mentioning that this work cannot be done with the keyword "manufacturing" in the inquiries as this closes the results to less than 40 documents in Scopus. This limited result could lead to a biased understanding of the research field and the actual trends and gaps being missed. Therefore, an independent review for each is attempted, and an examination of the intersection of both results is performed to understand the opportunity and trends for manufacturing research.

2. Research Methodology

An array of multiple academic papers, journals, and conferences was gathered to fulfill the objectives of this study. The Scopus database was used to obtain a collection of publications. A limitation of research scope was set, naturally, as the study cannot cover the entire universe of research articles [16,17]. The key points for each academic entity will be defined by its title, keywords, abstract, and main contributions. This article's methodology is discussed below, and visual aid is found in Figure 1.

2.1. Bibliometric Analysis

Any scientometric or bibliometric study will rely heavily on its data acquisition as this defines the academic articles from which any arguments will be derived. Therefore, the database selection and screening strategy have to be implemented meticulously. The Scopus database was chosen in this study because its literature source has an extensive range of coverage on the construction-related research subject compared to other literature databases such as PubMed, Google Scholar, and Web of Science [14,18,19]. Other academic databases cannot match Scopus for research in multidisciplinary fields, like the ones mentioned above, and Scopus has the advantage of possessing an extensive list of international academic journals. The current publications of cross-laminated timber (CLT) and Industry 4.0 connected to the construction industry in the database used for this analysis were recovered by using keywords, i.e., "cross-laminated timber*", "4.0 industry*", and "construction*" (the wild character * is implemented to acquire variations of the same word, such as "cross-laminated timber" or "mass timber"). To fulfill the goal of this article and to narrow the results obtained, the keywords used were: ({Cross-laminated timber} OR {Cross-Laminated Timber} OR "Cross-laminated timber*") AND ("construction*"); ("Industry 4.0*") AND ("construction*"). Note that Scopus use curly brackets ({}) for a specific word search. The inquiries were made in two different sets because otherwise the result would not pass 100 documents.

The keyword search in the literature database was implemented as "title/abstract/keyword", so all the entities with the keywords matching the criteria above in the title, abstract, or author-defined keyword section were retrieved. The inquiry was closed for the last 20 years, from March 2002 to April 2022; however, the results obtained show a first appearance since 2006 and an increasing trend in the research field, showing the importance and interest for CLT in the construction research field. Therefore, the inquiry for Industry 4.0 was limited to the same period for coherence. A scrutiny search on the array of publications was conducted to purify the results obtained and remove anything unrelated to the engineering scope. An example is the keyword "CLT", which was used in initial inquiries, yet was later removed as it brought a vast number of publications in the subject area of mathematics, having a different acronym interpretation in this field. The scope of this study was closed to exclusively entities from peer-review English journals or conference proceedings. An additional cleaning process was performed on the remaining entities of the inquiry; in this step, the title and abstract were inspected manually to remove any paper from an irrelevant journal or conference proceeding. The academic data were used for the bibliometric analysis once the entire set was cleaned. For a more precise understanding, the initial results given by Scopus were over 2000 documents just for the CLT inquiry, but it was refined to 817 with the first change on search criteria; then, it was refined to 753 after the manual screening, namely 403 journal papers and 350 conference papers. The irrelevant journals removed were excluded thanks to the subject area or the different context of the acronym "CLT" in mathematics.

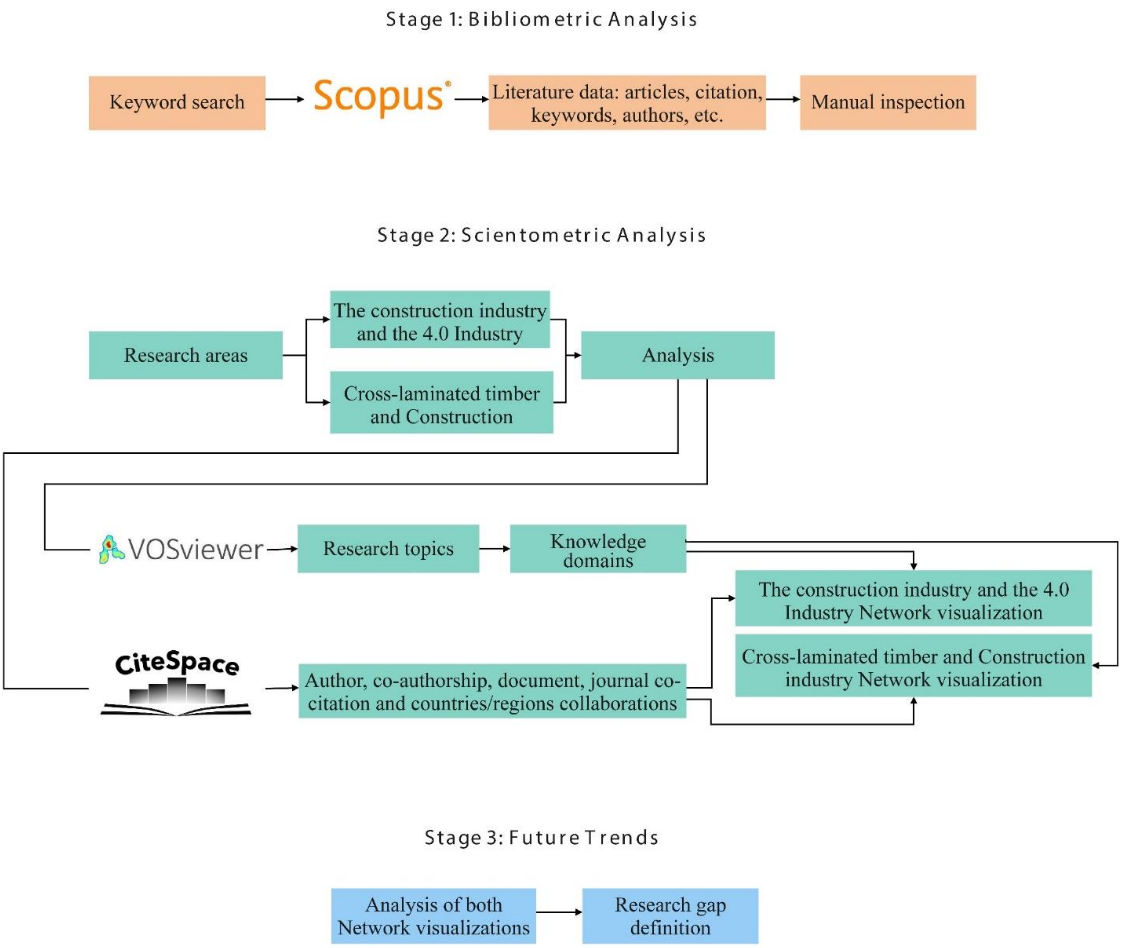

Figure 1. Overall view of the suggested research methodology.

2.2. Scientometric Analysis

Scientometrics is considered a sub-field of informetrics, and it can be defined as a technique that measures and analyzes scholarly literature [20]. Scientometric studies can be found since the 1970s in the literature, and scientometrics has been applied to multiple research subject areas, such as medicine, physics, and astronomy [21–23]. There are multiple research topics for cross-laminated timber and Industry 4.0 in construction. It will be complicated to obtain an overall representation of both fields with a traditional literature review. Even though manual reviews provide knowledgeable critical synopsis of any research field, they are limited to the number of publications one author could consider [24,25]. Thus, this article suggests a comparative review of CLT and Industry 4.0 in construction-related publications with the aid of scientometric analysis to obtain a clear visualization and mapping of the research areas. The technique includes bibliometric tools for academic journals and conferences and is used to graph its framework and development on diverse topics, thanks to the big academic dataset. With the help of network modeling and graphs, the scientometric method targets evaluating the big picture on the research knowledge and tries to provide questions that researchers may further investigate in later studies, along with techniques the scientists have used to fulfill their goals. Mapping the overall work on cross-laminated timber and Industry 4.0 for construction will allow lecturers to understand the global mindset of academic patterns and tendencies in the fields. In academic content, it is considered that keywords and abstracts provide a well-defined and terse description of the work they are included in, and it is common to use keywords as pieces of analysis to detect highlighted groupings that may affect the structure of the researched field. This paper analyzes the literature on CLT and Industry 4.0 in construction in terms of keywords and abstract terms to understand the researchers' options as much as possible. The following research techniques were enforced to obtain academic patterns: keyword co-occurrence analysis and clustering, country co-occurrence and co-citation, co-author and burst detection, and abstract term cluster analysis. The study starts with keyword and author co-occurrence analysis which gives an accumulated representation of the entities and the nodes in the network map to supply evidence for the next clustering analysis. Next, the burst detection provides deeper insight into the relative adjustments over time to identify tendencies and differences in CLT and Industry 4.0, contrary to the prior analysis that only gave a static picture of the entire research field. In addition, abstract term clustering shows investigation patterns within the field with more scrutiny and highlights different associated research topics to outline the research conceptual structure. These scientometric methods have been endorsed in former similar studies.

2.3. Future Trends

Future trends indicate the technologies or developments that will occur in the not-too-distant future, allowing us to understand and analyze what is required to reach that step forward [26]. Understanding trending topics in the current state of the academic field will allow readers to understand which subjects are highly relevant within these domains. The study started by delimiting the research into two subjects: the construction industry and Industry 4.0; the cross-laminated timber and construction industry. It was decided to delve only into cross-laminated timber in construction for the purposes of this analysis. The cluster analysis of the construction industry and Industry 4.0 was delimited because it covers a large number of topics that are not relevant to the intention of this research; by going too profound, it will be difficult to obtain the main trending topics of this area. This paper used the network visualizations obtained from CiteSpace and VOSviewer to analyze the clusters captured and a comparative review between them to understand the relationships between the different trending topics, understanding a network visualization as a graph of connected entities with links and nodes. The resolution of the trending topics of both research areas was used to examine the intersection between them and thus define the research gap.

3. Results for Cross-Laminated Timber in Construction

3.1. Data Acquisition

In the first search strategy, keywords, as mentioned above in Section 2, were used to identify pertinent academic papers in journals and conferences; a summary of the most relevant results is shown in Table 1. Most of the articles lay in journals for structural engineering, covering both the CLT and construction research fields, including *Engineering Structures*, *Bautechnik*, and *Journal of Building Engineering*. The second type of journals found in the array is those for material properties, such as *Construction and Building Materials*, *Wood and Fiber Science*, and *Applied Acoustics*. Additionally, there is a substantial appearance of journals for sustainability, such as *Sustainability* (Switzerland), *BioResources*, and *Building and Environment*.

Among all the sources, World Conference on Timber Engineering is the conference proceeding with the highest number of contributions, 168 publications which cover 48% of all the conferences, and it even surpasses the biggest academic journal, which has only 36 articles. Two other relevant proceedings are the International Congress on Noise Control Engineering and International Association for Bridge and Structural Engineering (IABSE), providing 23 and 19 articles, respectively, both being on the list of top contributors for this field. Remarkably, a great part of the publications found held fewer than four articles related to this field: 40.45% of the academic journals and 24.29% of the conference proceedings were published in this condition.

Table 1. List of most broadly read academic journals and conference proceedings from January 2006 to March 2022 that had publications related to cross-laminated timber in construction.

Journal Title	**Number of Articles**	**% Total Publications**
Engineering Structures	36	8.93%
Construction and Building Materials	33	8.19%
Journal of Structural Engineering (United States)	19	4.71%
Bautechnik	15	3.72%
Journal of Building Engineering	15	3.72%
Sustainability (Switzerland)	14	3.47%
BioResources	12	2.98%
Buildings	12	2.98%
Energy and Buildings	9	2.23%
Structures	9	2.23%
European Journal of Wood and Wood Products	8	1.99%
Wood and Fiber Science	8	1.99%
Journal of Structural and Construction Engineering	7	1.74%
Building and Environment	6	1.49%
Journal of Materials in Civil Engineering	6	1.49%
Journal of the Korean Wood Science and Technology	6	1.49%
AIJ Journal of Technology and Design	5	1.24%
Journal of Architectural Engineering	5	1.24%
Journal of Cleaner Production	5	1.24%
Structural Engineer	5	1.24%
Wood Material Science and Engineering	5	1.24%
Applied Acoustics	4	0.99%
Applied Sciences (Switzerland)	4	0.99%
Energies	4	0.99%
Conference Title	**Number of Articles**	**% Total Publications**
World Conference on Timber Engineering	168	48.00%
International Congress on Noise Control Engineering	23	6.57%
IABSE—International Association for Bridge and Structural Engineering	19	5.43%
International Conference on Structures and Architecture	12	3.43%
Annual Conference of the Canadian Society for Civil Engineering	10	2.86%
Nordic Symposium on Building Physics	8	2.29%
International Congress on Sound and Vibration	6	1.71%

Table 1. *Cont.*

Journal Title	Number of Articles	% Total Publications
Structures Congress	6	1.71%
International Conference of the Association for Computer-Aided Architectural Design Research in Asia	5	1.43%
International Congress on Acoustics	4	1.14%
International Conference on Structural Engineering, Mechanics and Computation	4	1.14%
International Conference and Exhibition on Fire and Materials	3	0.86%
Australasian Conference on the Mechanics of Structures and Materials	3	0.86%

A graph of the timeline with the number of publications per year is presented in Figure 2; this includes both academic journals and conference proceedings. As a note, the search was performed looking for any articles from the last 20 years (starting on 2002), but the earliest article was found from 2006. This figure shows a clear upward trend of publications that started to rise in 2010, allowing us to say that cross-laminated timber is of great interest to the construction industry. There are two time slots that show a clear spike in publications: first, between 2015 and 2016, the number of articles almost tripled between one year and the other; second, between 2017 and 2018, the publications had a 117% increase from the previous year. Curiously, the International Building Code (IBC) started to recognize CLT products in 2015 for their use in primary structural elements (beams, columns, floors, etc.) [27,28]. Additionally, it is important to mention that this graph shows a number of 17 publications for 2022; however, making an interpolation, we could estimate the number of 169 articles and conferences for the entire year.

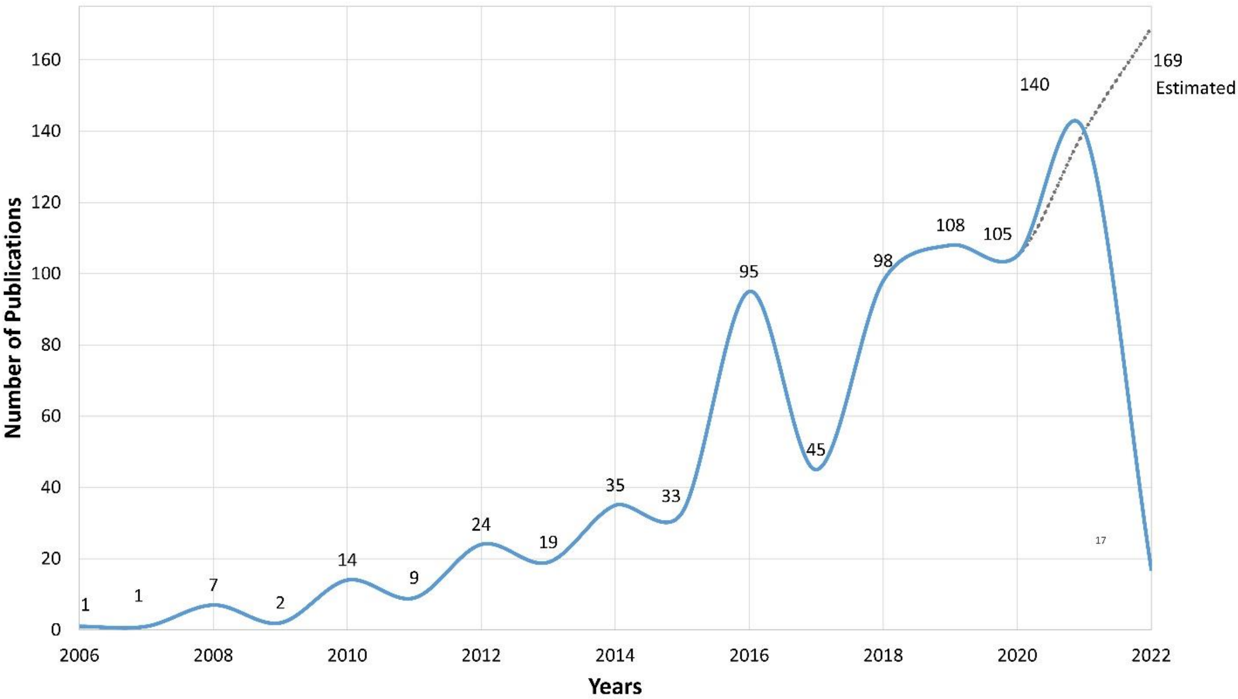

Figure 2. Historical trend of published studies in cross-laminated timber (CLT) for construction (period 2006–2022).

3.2. Keyword Co-Occurrence Analysis

Authors use keywords to represent the main content of the published articles and to display the scope areas researched within the limits of any domain [29,30]. In this study, the keyword co-occurrence analysis in the research area of cross-laminated timber and construction was generated with the VOSviewer software. The bibliometric analysis results of the literature are displayed with a keyword's network. The map generated by VOSviewer is a distance-based network where the space between nodes represents the strength of the relation between two knowledge domains [31,32]. A longer distance usually implies a weaker bond between the two nodes. The node or item label size is directly proportional to the sum of articles where the keyword was found. Different colors represent different groups of knowledge obtained with the clustering technique of VOSviewer [33,34]. The threshold for the minimum number of occurrences was 20, so 73 of the 4872 keywords meet these criteria for a node. The threshold of 20 was selected based on the multiple iterations with different parameters to obtain optimal clusters. The network map for the co-occurrence keywords is shown in Figure 3. This map has 73 nodes, 1885 links, and a total link strength of 9543. A summary of keyword data for the network map can be found in Table 2, where the average published year, the number of links, and strength are placed.

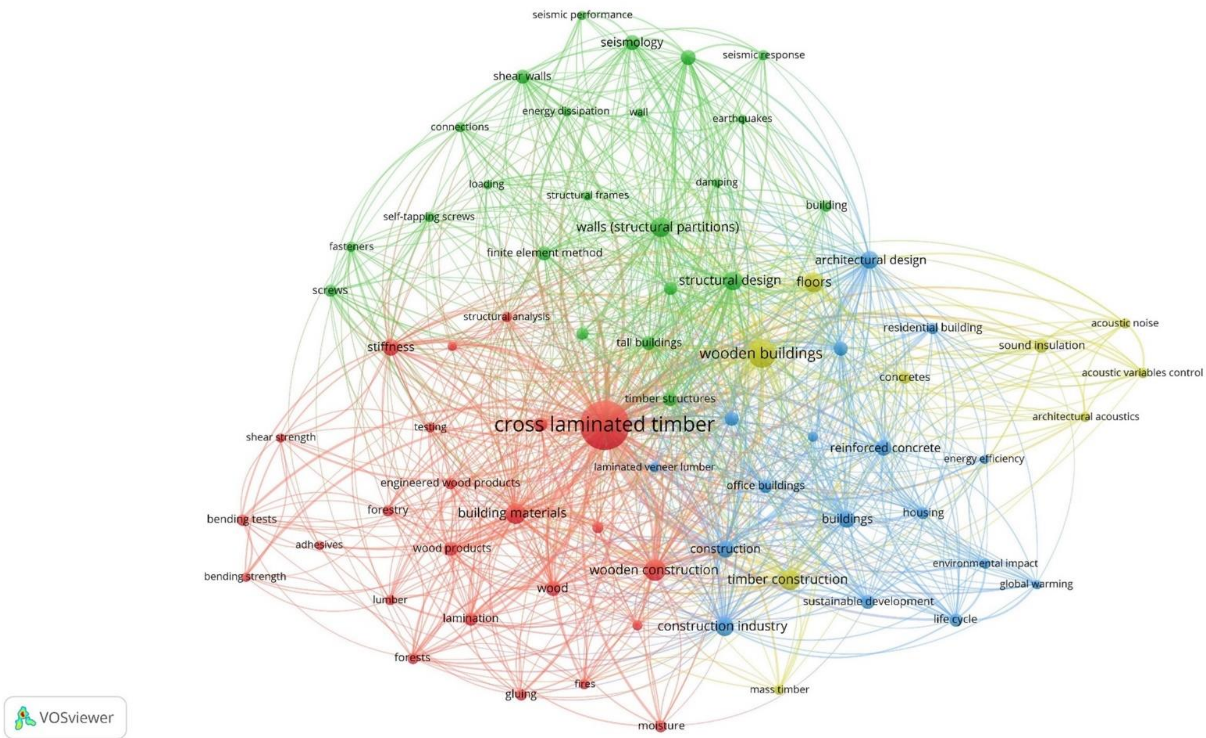

Figure 3. Network map of co-occurring keywords related to cross-laminated timber in construction (2006–2022).

Each keyword has an occurrence number attached to it, as shown in Table 2, and this metric represents the times this search word was retrieved from the academic dataset in the author keywords. For instance, aside from the principal keyword "cross-laminated timber", the second keyword with 172 occurrences is "wooden buildings", meaning that researchers had spent extensive time looking into this field. Another important metric provided in Table 2 is the average year published, which represents the average time period where a certain keyword was used by authors in their articles. Notably, between the years 2014 and 2016, one could find 11 keywords, such as "buildings", "design", and "residential building", indicating the initial interest of researchers in the use of CLT in construction. On the other hand, it is possible to find 15 keywords just in the year 2019, and the results show words such as "stiffness", "bending strength", and "moisture", showing the academic interest in determining the characteristics of CLT as construction material. Additionally, there are significant keywords showing up this year, such as "life cycle", "environmental impact", and "global warming", highlighting the interest of researchers in a more sustainable material in this field. The metric "links" represents the number of linkages between a specific node and others, and the total link strength indicates the total strength counted for a certain node [35]. For example, the total link strength of "structural design" is 686, positioning this keyword in the top list among all the keywords, showing a substantial relation between cross-laminated timber and structural design.

Network maps are usually a static representation of data that does not consider changes in a timeline, including keyword co-occurrence; however, VOSviewer is able to include a color-code-based network overlaid on the same map of the keyword co-occurrence to show the transition of the nodes based on the average year of each keyword. Thus, Figure 4 represents the evolution of cross-laminated timber in the construction industry over the last 16 years. As a note, not all the keywords extracted from the literature are included in the network, as only those representative words with an occurrence of 20 are displayed. This constraint, curiously, reduced the span of time provided by VOSviewer and forced the map to start in the year 2016, just one year after the acceptance of CLT in the International Building Code. Looking at the map, it is possible to notice general words such as "buildings", "residential building", "fasteners", and "design" as the first keywords related to 2016, indicating the beginning of research in these fields. For the middle spectrum, between 2017 and 2018, keywords such as "seismology", "structural design", "walls (structural partitions)", and "lamination" are highlighted. These keywords express the interest of academic authors in the understanding of the general mechanics of CLT as a construction material. Peculiarly, keywords in the late years, near 2019, are closer to dedicated or specific mechanics of the material; examples include "shear walls", "shear strength", "bending stress", and "finite element method". In addition, keywords as "life cycle", "global warming", "energy efficiency", and "environmental impact" have a meaningful appearance in the last years, showing how construction is moving towards a sustainable industry and how this industry considers cross-laminated timber as an alternative sustainable material.

Table 2. List of selected keywords and relevant network data.

Keyword	Occurrences	Average Year Published	Links	Total Link Strength
Cross-laminated timber	546	2018	111	3698
Wooden buildings	172	2018	109	1428
Wooden construction	107	2018	103	918
Building materials	94	2017	103	786
Timber construction	94	2017	98	660
Walls (structural partitions)	90	2018	105	751
Floors	85	2017	102	682
Structural design	83	2018	102	686
Construction industry	82	2018	102	646
Architectural design	71	2018	97	619
Construction	68	2017	103	588
Buildings	66	2016	98	600
Stiffness	65	2019	93	533
Reinforced concrete	56	2018	86	441
Wood	54	2017	101	475
Seismology	50	2018	80	409
Seismic design	49	2018	81	457
Finite element method	48	2018	88	371
Shear walls	48	2018	73	391
Timber buildings	48	2018	85	408
Building codes	47	2017	95	415
Laminated composites	47	2018	101	425
Tall buildings	46	2017	101	445
Timber structures	46	2017	97	363
Wood products	46	2017	86	415
Sound insulation	45	2017	58	296
Sustainable development	45	2018	76	363
Lamination	40	2017	81	366
Office buildings	39	2017	84	318
Design	38	2016	92	341
Life cycle	38	2019	65	319
Housing	36	2018	68	301
Moisture	35	2019	52	209

Table 2. *Cont.*

Keyword	Occurrences	Average Year Published	Links	Total Link Strength
Concretes	33	2017	87	289
Building construction	32	2018	78	252
Screws	32	2017	77	275
Residential building	31	2016	78	260
Engineered wood products	30	2017	76	291
Forests	30	2014	77	300
Gluing	30	2018	66	254
Bending tests	28	2019	55	200
Building	28	2019	77	215
Forestry	28	2017	65	202
Product design	28	2017	71	235
Fire resistance	27	2017	71	218
Architectural acoustics	26	2016	40	165
Fasteners	26	2016	67	224
Laminated veneer lumber	26	2018	75	224
Lumber	26	2018	72	228
Self-tapping screws	26	2018	67	212
Environmental impact	25	2019	55	199
Structural systems	25	2016	67	203
Connections	24	2016	66	225
Fires	24	2016	62	203
Mass timber	24	2019	58	165
Seismic response	24	2019	59	206
Testing	24	2017	67	198
Acoustic noise	23	2017	38	173
Acoustic variables control	23	2016	39	167
Structural analysis	23	2016	68	223
Bending strength	22	2019	43	145
Earthquakes	22	2017	64	205
Adhesives	21	2019	49	130
Damping	21	2018	59	162
Energy efficiency	21	2019	46	122
Global warming	21	2019	50	195
Loading	21	2019	63	190
Seismic performance	21	2018	52	156
Structural frames	21	2017	59	181
Structural performance	21	2017	67	182
Wall	21	2019	63	210
Energy dissipation	20	2018	51	157
Shear strength	20	2019	58	154

3.3. Co-Author Co-Occurrence Analysis

The academic data obtained from Scopus have multiple properties available from the articles, including the information of the authors; this allowed us to perform an analysis of the principal researchers working in this field and the collaboration among them. Thus, a network map similar to the keywords could be generated but for co-authorship instead. Table 3 shows the top 10 leading researchers in this field, using the number of publications in the dataset; M. Shahnewaz (Fast + Epp and University of Northern British Columbia), C. Loss (University of Northern British Columbia), and A. Polastri (National Research Council of Italy) are listed as the first three positions.

Network maps are helpful for visualizing and analyzing academic data because authors can capture the logic and behavior in the body of knowledge [36]. Otherwise, they will have to rely on their reading and biased systematic reviews. It is necessary to use visualization tools for this purpose. CiteSpace allows the user to generate maps different from keyword networks [36], which are needed to scrutinize the extensive amount of data from the academic dataset, making CiteSpace an advantageous software for scientometric analysis. Thus, this instrument was used to obtain and evaluate the network map for co-authorship, country co-occurrence, co-citations, and abstract clustering. In addition, CiteSpace allows showing a burst detection graph based on Kleinberg's work, which helps detect the frequency of abrupt change in a specific time gap of any entity [37].

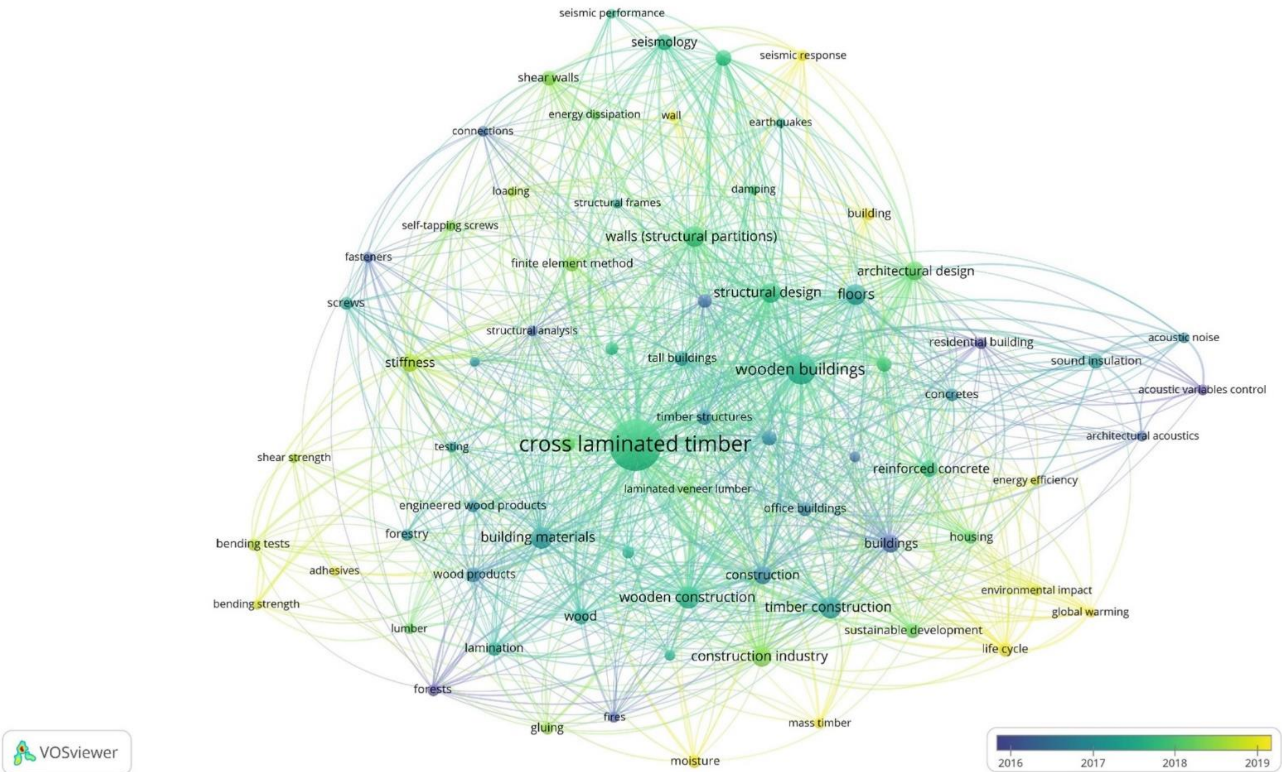

Figure 4. Time-based network of co-occurring keywords showing the evolution of nodes based on the average year for CLT in construction.

Table 3. List of the top 10 most productive authors in the 2006–2022 time period for CLT in construction.

Author	Institution	Country	Count	Percentage
T. Tannert	University of Northern British Columbia	Canada	18	2.390%
S. Pei	Colorado School of Mines	USA	15	1.992%
De. Van	Colorado State University	USA	12	1.594%
Ar. Barbosa	Oregon State University	USA	10	1.328%
A. Sinha	Oregon State University	USA	9	1.195%
I. Smith	University of New Brunswick	Canada	8	1.062%
M. Popovski	FPInnovations	Canada	7	0.930%
X. Li	Deakin University	Australia	6	0.797%
A. Polastri	National Research Council of Italy	Italy	6	0.797%
M. Fragiacomo	University of L'Aquila	Italy	6	0.797%

The network map for co-authorship is presented in Figure 5. Each node represents an author, and the link among them is the collaboration or the so-called co-authorship in publications. Not all the authors are shown in the picture to maintain cleanliness, and the number of nodes was reduced through Pathfinder, a recommendation by the author of CiteSpace [38]. The map generated possesses 338 nodes and 414 links. The size of each node is proportional to the author's number of publications. The thickness of the link is linked to the level of collaboration between researchers; see Table 4 for the general parameters of this graph. Among the multiple parameters given by CiteSpace, modularity Q and mean silhouette help in understanding the frame properties of the network. First, modularity Q, measuring the quality of grouping in a network, has a high coefficient (0.7856), meaning that the map generated is well spread in loose groups [39,40]. The second parameter, mean silhouette, has a coefficient of 0.9443, meaning that the clusters found in the network are well-defined or heterogeneous [41].

Figure 5. Co-authorship network map for academic articles for cross-laminated timber in construction.

Table 4. General parameters of the co-authorship network.

Network	Nodes	Links	Density	Modularity Q	Mean Silhouette Score
Co-authorship	338	414	0.0073	0.7856	0.9443

As shown in Figure 5, the authors with more collaborations are displayed with a bigger circle in their node than the others; the bigger the size, the strongest the collaboration, where researchers such as T. Tannert, J. W. van de Lindt, S. Pei, and A. Barbosa represent the lead circle of authors. Nevertheless, even the strongest researcher covers less than 3% of the publications for CLT in construction, meaning that more international academic teamwork will benefit this field. On the other hand, using the "centrality" parameter, defined as a function of the sum of all the minimum distances between a node and all others [42], we could see that T. Tanner (centrality = 0.12) has the highest score in this network. Yet, this number is incredibly small and suggests more collaborations again among researchers. It is possible to find other critical contributors by using the burst detection tool in CiteSpace, where the author burst identifies entities with a high number of citations in a small period of time. The results show that S. Gagnon (burst strength: 1.78, 2009–2013) and I. Smith (burst strength: 1.72, 2014–2018) had a burst of 4 years; however, A. Polastri (burst strength: 2.54, 2016–2018) and R. Brandner (burst strength: 2.54, 2016–2018) had a stronger burst in half the time. These contributors had great attention in their period of time, and it is worth mentioning S. Liang (burst strength: 1.99, 2020–2022) and H. Gu (burst strength: 1.59, 2020–2022), who have been rising to be lead authors in this field in the last 2 years. The fact that these two last authors have been researching in this field in the last years indicates the importance of CLT in construction, but the centrality metric and the node sizes still suggest higher collaborations among researchers.

3.4. Network of Countries/Regions and Institutions

A network was created to visualize how research publications on cross-laminated timber for construction are distributed in different countries. This network is made up of 51 nodes and 95 links. Figure 6 shows five countries with the highest contribution of publications in this area: the USA with 77 articles, where the authors who contributed the most cited articles are Shiling Pei, Ryan Ganey, and Omar Espinoza; Canada with 68 articles, where the most cited authors are Lin Wang and John W. van de Lindt; Italy with 48 articles, where the top authors are Cristiano Loss and Thomas Reynolds; and China with 42 articles, where most relevant authors are Minjuan He, Haibo Guo, and Ying Liu with the most cited papers in the research field. In the CiteSpace tool, nodes have centrality levels in the interval [0, 1]. Nodes with high centrality are represented with an outer purple ring, indicating that they are connected to at least two or more large groups of nodes. In this analysis that can be seen in Figure 6, it is shown that the countries with a key position are Austria (centrality = 0.31), Canada (centrality = 0.31), and Italy (centrality = 0.29).

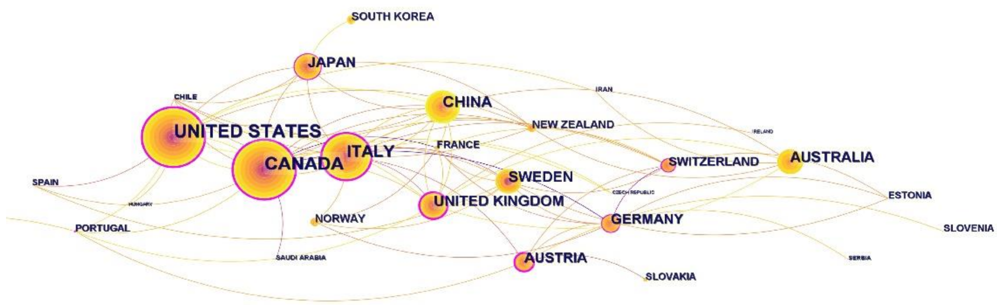

Figure 6. Network of countries/regions for publication of CLT in construction from 2006 to 2022.

When there is a sudden high increase in research over a period of time, in CiteSpace, it is indicated as a citation burst (see Figure 7). Aside from Switzerland, the rest of the countries have not heavily researched cross-laminated timber in construction for more than two years. However, it is noticeable how all the nations have given importance to this field since 2016, matching with the integration of CLT as a primary structural element in 2015 for the International Building Code (IBC). In Figure 7, it can be seen how from 2016, the research focus began to increase, leaving the latest bursts from 2020 until today's year (2022). Furthermore, the institutions' contributions regarding cross-laminated timber for construction were also identified. The institutions/faculties most involved and active in publications are the University of Auckland (28 publications), the University of Trento (22 publications), and RMIT University (19 publications).

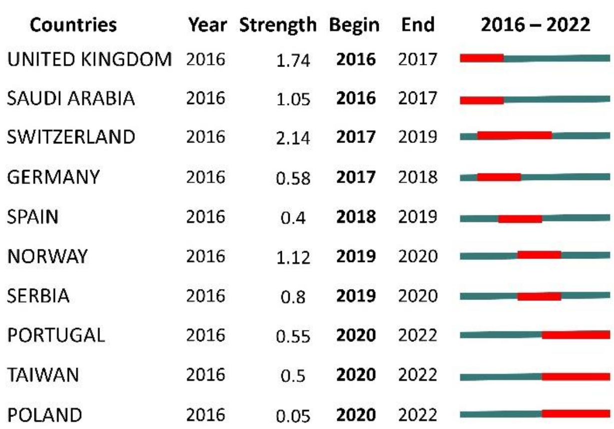

Figure 7. List of the relevant countries with citation bursts in the 1999–2019 time period.

3.5. Author Co-Citation Network

A co-citation network was generated to visualize the most important authors in the research area on cross-laminated timber for construction. Figure 8 shows the network made up of 281 nodes and 777 links. In this representation, each node means the number of times each author has been cited. The links generated between each author speak for the collaborations made between the authors. The authors identified as the most relevant in this network are Thomas Tannert, with 18 research collaborations that have a total of 175 citations; Shiling Pei, with 15 articles that have received a total of 429 citations; and John W. van de Lindt, with 13 records and a total of 341 citations.

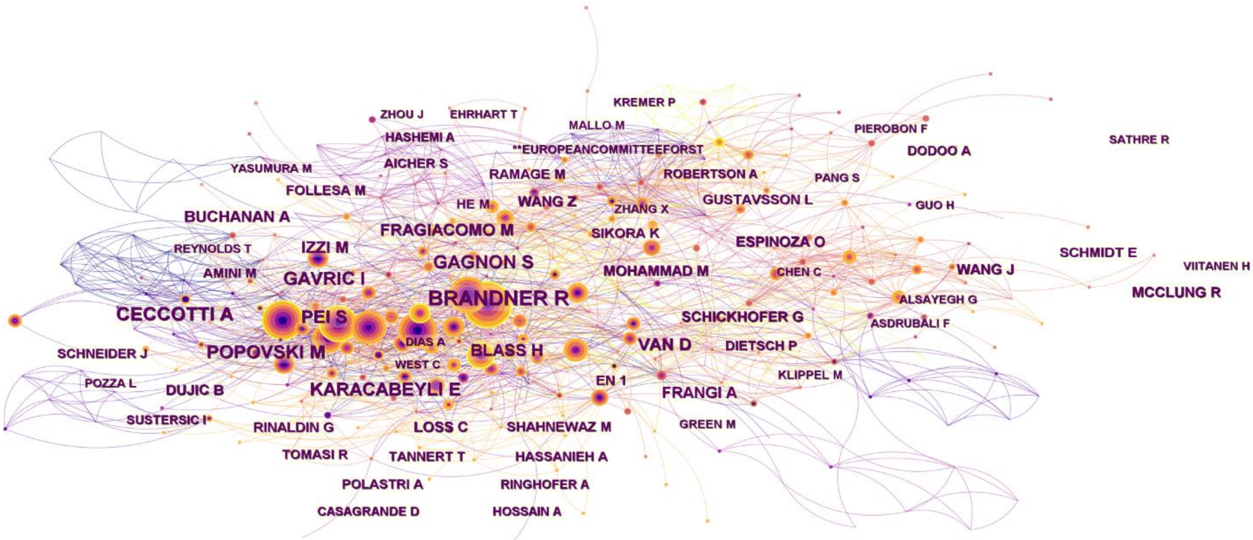

Figure 8. Author co-citation network for publications of cross-laminated timber in construction.

Moreover, regarding the top 10 most cited authors represented between 2006 and 2022 in Figure 9, a particular case can be observed where Sylvan Gagnon, with only three articles, had one of the longest bursts, with a duration of 4 years. This is directly related to the low level of importance that existed in the area of CLT panels in the construction industry at that time. The peak had not yet arrived, and this area had only started to be slightly investigated; despite the fact that Gagnon did not contribute a large number of articles, his contribution was one of the first and most relevant to further research in the area of cross-laminated timber for construction.

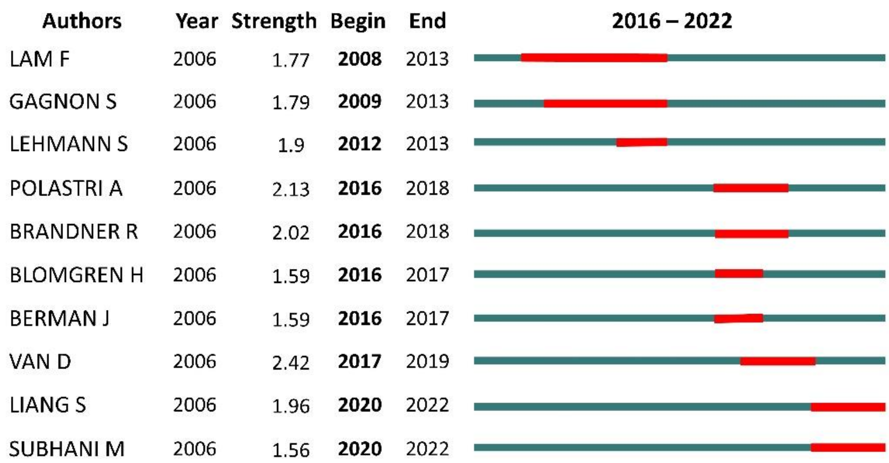

Figure 9. List of the top authors with relevant co-citation bursts.

3.6. Journal Co-Citation Network

For a better understanding of the research of cross-laminated timber in construction and as a complement to Table 1, where the leading academic journals and conference proceedings are identified from the Scopus data, a journal co-citation network map was generated with a result of 535 nodes and 2458 links (see Figure 10). A node's size represents the co-citation frequency for journals or conferences in this map. The most prominent entities were *Construction and Building Materials* (frequency of 120), *Engineering Structures* (frequency of 102), *Journal of Structural Engineering* (United States) (frequency of 83), *Energy and Buildings* (frequency of 50), *Building and Environment* (frequency of 59), *European Journal of Wood and Wood Products* (frequency of 47), *Journal of Materials in Civil Engineering* (frequency of 39), and *Sustainability* (Switzerland) (frequency of 37). The results are fairly similar to the top sources for CLT in construction. Peculiarly, the centrality was calculated, and the three top journals changed compared to the frequency table. The first entity was World Conference on Timber Engineering, the second was International Association for Bridge and Structural Engineering (IABSE), and the third was *Engineering Structures*. This result suggests that conference proceedings are highly used by researchers, where conference articles cite other academic journals; however, academic journals do not often cite conference proceedings. It is worth mentioning that the journals related to cross-laminated timber in construction are mainly focused on structural research, followed by material engineering and others with worthy participation in sustainability.

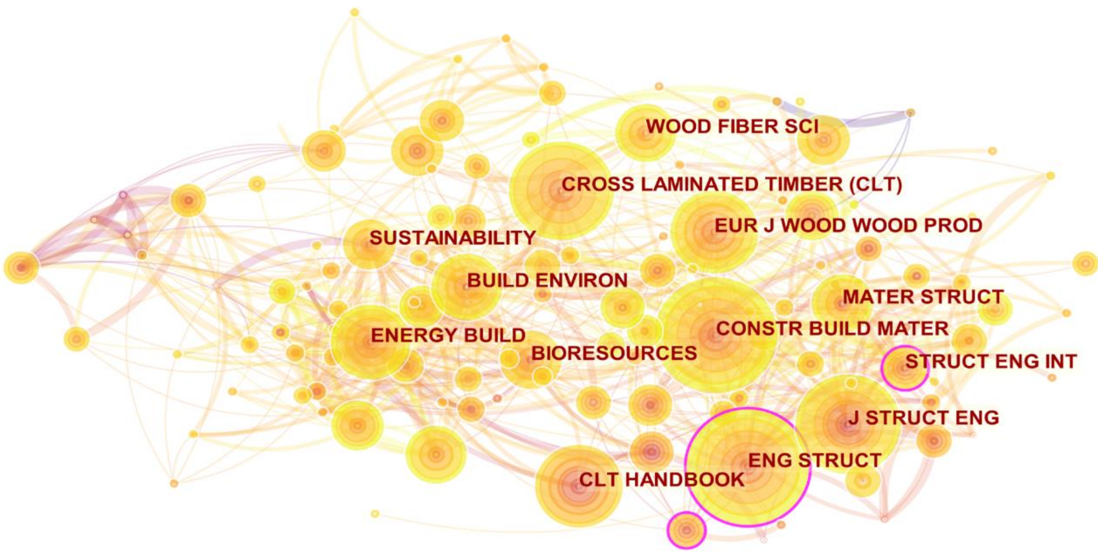

Figure 10. Journal co-citation network map related to cross-laminated timber in construction.

3.7. Document Co-Citation Network and Clustering

The subsequent analysis is document co-citation, which helps understand the relationship of one entity among others, academic articles in this case. This analysis allows us to understand the base knowledge structure and determine the quantity and relevance of references used by researchers. The network map was generated on CiteSpace, as shown in Figure 11. Additionally, CiteSpace allows the user to sort the publications, and the most relevant list is presented in Table 5. Here the article from Brandner stands out from the rest of the publications with 56 citations and a centrality of 0.20, represented with a more significant node and a purple outer ring in Figure 11 [43]. Yet, in general, all the documents have low centrality, meaning that there is no document central to the entire research field. To consider a publication central to the network, it must have a value above 0.3 [44].

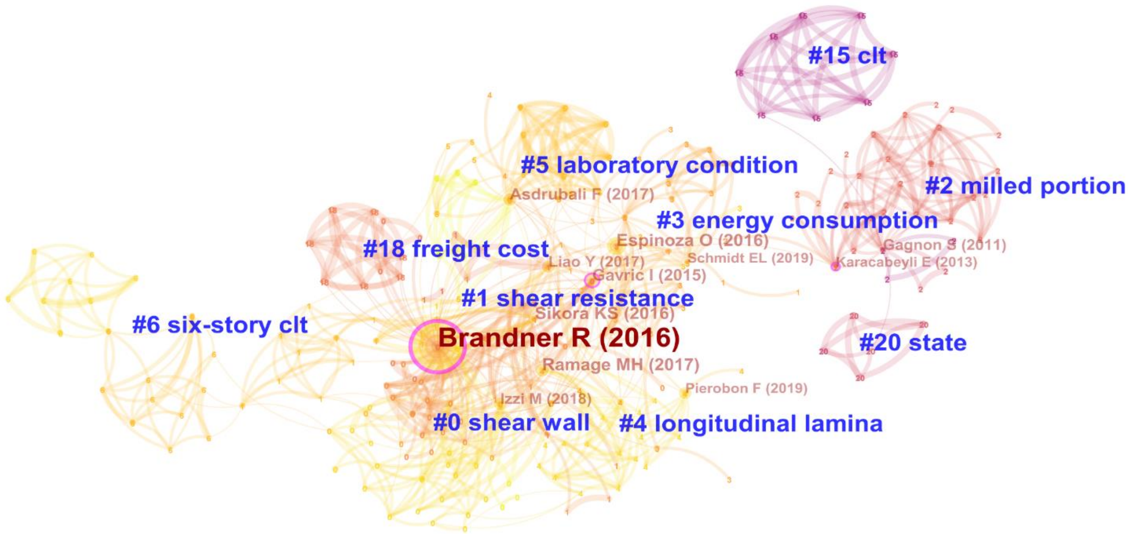

Figure 11. Abstract clustering network map of co-citations.

Table 5. List of the top 25 most cited articles between 2006 and 2022.

No.	Article	Total Citations	Centrality	No.	Article	Total Citations	Centrality
1	Brandner et al. [43]	56	0.20	14	McClung et al. [56]	6	0.03
2	Ramage et al. [45]	12	0.02	15	Ehrhart et al. [57]	6	0.00
3	Espinoza et al. [46]	11	0.03	16	Gavric et al. [58]	5	0.01
4	Sikora et al. [47]	11	0.02	17	Wang and Ge [59]	5	0.01
5	Gavric et al. [48]	9	0.15	18	Aicher et al. [60]	5	0.01
6	Asdrubali et al. [49]	9	0.04	19	Bita and Tannert [61]	5	0.03
7	Liao et al. [50]	8	0.02	20	Hassanieh et al. [62]	5	0.01
8	Gagnon et al. [5]	8	0.09	21	Ceccotti et al. [63]	5	0.01
9	Izzi et al. [51]	8	0.04	22	Shahnewaz et al. [64]	4	0.01
10	Karacabeyli and Gagnon [52]	7	0.14	23	Amini et al. [65]	4	0.05
11	Schmidt et al. [53]	7	0.01	24	He et al. [66]	4	0.00
12	Pierobon et al. [54]	7	0.01	25	Morandi et al. [67]	4	0.00
13	Jones et al. [55]	6	0.00				

As shown in Figure 11, the document co-citation map has 491 nodes and 1353 links, and it includes the clusters generated using the abstract terms. In this graph, each node represents a journal or conference proceeding where the label is taken with the first author's name and the year of publication. Each link symbolizes the co-citation connection between two publications, and the node size is proportional to the co-citation frequency. The clusters were generated using the abstract of each journal cited, resulting in a total of 10 groups. These clusters are well defined, but four are loosely gathered around the main body in the middle of the network. Table 6 presents the list of the clusters, including the IDs, the label given by CiteSpace, an alternative name deducted from the principal journal abstracts, and the leading representative publications.

It is possible to analyze the knowledge clusters for cross-laminated timber in construction with the data in Table 6 and the network map in Figure 11. Starting with the first clusters in the timeline, cluster #15 (mean publication year = 2009) and cluster #20 (mean publication year = 2011), it can be seen that these groups have a low number of publications related to them; still, it is essential to remember that academic articles were limited around that decade. There were years with only one publication associated with this field. For the same reason, there is no surprise that the first topics of researchers were related to the understanding of CLT as a new style of construction. For instance, in cluster #15, Crespell et al. conducted a study to understand CLT as an alternative construction material to concrete [68]; Popovski et al., from cluster #20, performed an analysis of CLT construction design according to the North American building code [69].

Table 6. Co-citation clusters of cross-laminated timber in construction from 2006 to 2022.

Cluster ID	Size	Abstract Cluster Label	Alternative Labels	Mean Publication Year	Representative Documents
#0	53	Shear wall	Seismic characteristics	2016	Polastri [70], Brandner [43]
#1	36	Shear resistance	Rolling shear/structural behavior	2016	Ehrhart [57], Oktavianus [71]
#2	32	Milled portion	Mechanical properties	2012	Gagnon [52]
#3	26	Energy consumption	Time/cost optimization	2016	Gasparri [72]
#4	24	Longitudinal lamina	Lamina properties	2017	Pang [73,74]
#5	22	Laboratory condition	Material properties/ energy performance	2017	Asdrubali [49], Wang [75]
#6	19	Six-story CLT	CLT in tall buildings	2017	Fitzgerald [75]
#15	8	CLT	Sustainability comparison/ CLT and concrete	2009	Crespell [68], Damtoft [76]
#18	7	Freight cost	Transportation analysis	2015	Passarelli [77]
#20	5	State	North America state	2011	Popovski [69]

The rest of the clusters are dedicated to understanding the mechanical properties and sustainability of cross-laminated timber in construction. The bigger group, cluster #0, focuses on seismic performance analysis in CLT, and part of the reason for this center of attraction is the growing usage of CLT in high-rise buildings (colloquially called "tall timber buildings") [70]. A clearer path of the growth of CLT in buildings begins with the seismic analysis performed by Ceccoti in 2008 for a three-story building [78]. This study is followed by that of Polastri et al., who studied the seismic performance in a seven-story building with CLT core and shear walls [70], and then the publication of Connolly et al. for the UBC tall wood building which has a height of above 53 m, obtaining the name of the world's tallest hybrid wood-based building in 2016 [79]. On the other hand, cluster #4 was dedicated to studying specific properties of CLT and the material behavior depending on the lamina composition. The authors were looking to understand the limits and behavior of the wood panels depending on their usage. For example, Pang conducted two studies: the first study aimed at understanding the bending strength and stiffness depending on the number of lamina combinations and the wood type and thickness [73]; the second study was on the analytics of the compressive resistance of CLT depending on the difference in lamina grade and aimed at having a more reliable way of prediction [74].

In the area of sustainability, there is cluster #5, where we could see how researchers were seeking a more environment-friendly solution for construction, and wood came as an evident response due to its excellent strength-to-weight ratio. The studies were initially on any wood variables, softwood, hardwood, and composites, but CLT stands up against others, and an understanding of its properties is needed. For this reason, Asdrubali et al. conducted a study to determine multiple characteristics of CLT, such as thermal, acoustic, and structural properties [49], and Wang et al. conducted a hygrothermal performance analysis to understand the long-term durability of CLT panels [59]. Additionally, cluster #18 gathered studies about the freight cost and its environmental impact. In this field, Passarelli researched the freight cost and environmental impact of transportation from the cradle up to the construction site, concluding that the CLT manufacturing plant must be as close as possible to the wood sources to reduce freight costs and the production of low-value-added products [77].

4. Results for Industry 4.0 in Construction

In the previous section, a review of the development of cross-laminated timber in construction was performed through a scientometric analysis. It showed the importance of the material in the last decade and how the authors have exhibited much interest in this field. The main research topics are dedicated to understanding the material and its mechanical properties as detected in the co-citation clusters, and some authors explored issues related to sustainability. Oddly, nothing was found associated with Industry 4.0, which has attracted great interest in the construction industry in the last decades [80]. Topics such as automation, machine learning, and cyber-physical systems were expected to appear in the inquiry, but it did not go as expected. For this reason, a brief scientometric analysis for the Industry 4.0 in construction will be performed to see the big picture of the research topics in this field. As a note, in the following section, definitions already written in previous sections such as co-occurrence, centrality, or co-citation will be avoided for the cleanliness of the article.

4.1. Data Acquisition

Similar to the previous analysis, the data were obtained from Scopus, the keywords used in the inquiry were *"industry 4.0"* and *"construction"*, the search was limited to the engineering field, the period was maintained to keep coherence from 2006 to 2022, and the document type was limited to journals and conference proceedings. Once the files were ready, and after a manual clean-up, the number of publications was 567 documents. The academic journals and conference proceedings were plotted in a timeline to see the interest of researchers in this field, and the graph is presented in Figure 12. This figure shows a clear upward trend of publications, confirming the expected interest of researchers in Industry 4.0 in construction. More interesting is that the inflection point occurs in a similar period to that of CLT, around 2016. Before continuing, it is essential to mention that an inquiry in Scopus was made, including the keyword *"cross-laminated timber"*, but surprisingly, the results gave only two publications. The first paper from Biaconi et al. used generative models and evolutionary principles for an algorithm that allows the mass customization of single-family-size houses using CLT [81]. Their method allows having an automated design of small buildings of CLT and helps architects and engineers to reduce the developing time of this type of project. The second article, from Colella and Fallacara, presented a case study of a CLT house in the Mediterranean, Ecodomus, where they implemented intelligent design techniques and digital manufacturing tools for the building, making apparent the necessity for new technology for mass customization [82].

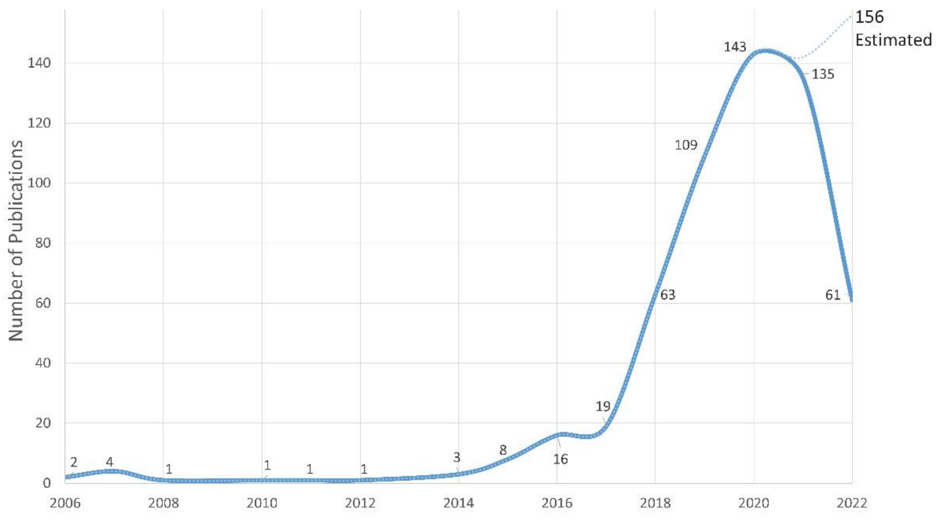

Figure 12. Historical trend of published studies in Industry 4.0 for construction (period 2006–2022).

The top 10 journals and conference proceedings were obtained from the academic dataset, similar to the previous Section, and the list is presented in Table 7. The journals with more coverage on topics of Industry 4.0 in construction are *Buildings*, *Applied Sciences* (Switzerland), *Automation in Construction*, and *Smart and Sustainable Built Environment*. On the conference side, the entities with more coverage are the International Symposium on Automation and Robotics in Construction; International Seminar on Industrial Engineering and Management; Annual Conference of the International Group for Lean Construction; and Smart Structures and NDE for Industry 4.0, Smart Cities, and Energy Systems. In contrast to Table 1, the publishers do not surpass more than 4% either in journals or conference proceedings; for instance, the leading conference covers only 3.14% of the publications, while on the other hand, the WCTE conference had almost half of the entire population for CLT in the construction. This means that no entity has obtained a strong position yet in this field, and the publications are still published homogeneously. Additionally, it is worth mentioning that Switzerland has appeared as a leading country for journals in both tables, *Applied Sciences* (Switzerland) for Industry 4.0 and *Sustainability* (Switzerland) for cross-laminated timber.

Table 7. List of the top 10 academic journals and conference proceedings from January 2006 to March 2022 covering publications related to Industry 4.0 in construction.

Journal Title	Number of Articles	% Total Publications
Buildings	12	3.82%
Applied Sciences (Switzerland)	10	3.18%
Automation in Construction	10	3.18%
Smart and Sustainable Built Environment	9	2.87%
Structural Integrity	8	2.55%
Construction Innovation	7	2.23%
IEEE Access	6	1.91%
IEEE Transactions on Industrial Informatics	6	1.91%
Advances in Science, Technology and Innovation	5	1.59%
Energies	5	1.59%
Conference Title	**Number of Articles**	**% Total Publications**
International Symposium on Automation and Robotics in Construction	8	3.14%
International Seminar on Industrial Engineering and Management	6	2.35%
Annual Conference of the International Group for Lean Construction	6	2.35%
IEEE International Conference on Automation/ 23rd Congress of the Chilean Association of Automatic Control	5	1.96%
Smart Structures and NDE for Industry 4.0, Smart Cities, and Energy Systems	5	1.96%
International Conference on Flexible Automation and Intelligent Manufacturing	5	1.96%
Annual Conference on Association of Researchers in Construction Management	4	1.57%
World Tunnel Congress	4	1.57%
International Conference on Innovation in Engineering	3	1.18%
International Workshop on Intelligent Computing in Engineering	3	1.18%

4.2. Keyword Co-Occurrence Analysis

Once the data were obtained from Scopus and the quick analysis of the journals and conferences was performed, the software VOSviewer was used to plot the keyword network for Industry 4.0 in construction. The threshold was set to 13 minimum occurrences in this network, obtaining 56 of the 4733 keywords. Like the previous analysis, the threshold was set after different iterations to find the optimal network. Figure 13 displays the network for the co-occurrence keywords. This map has 56 nodes, 994 links, and a total link strength of 3209. As shown in Table 8, the two keywords with high occurrences after "industry 4.0" and "construction industry" are "internet of things" and "architectural design", highlighting the topics authors have used the most in this field at this date. An additional parameter given by the VOSviewer is the average year of publication. Looking at Table 8 with the most relevant keywords, it is possible to see that all of them have gained relevance in the last three years, from 2019 to 2021. This matches with the trend found in the historical graph in Figure 12. Moreover, keywords such as "life cycle" and "sustainable development" surface in this analysis, similar to CLT results, meaning that sustainability is a topic of interest in both fields.

It is possible to see that "industry 4.0" and "construction" are the most relevant keywords in Figure 13. They are positioned in the center of the map and are bigger in size, and the rest of the keywords emerge from the two of them. It is interesting how a new keyword, "Construction 4.0" was generated from the interaction of these two fields. However, this node is still tiny compared to the other nodes, meaning this new definition is still in development. The co-occurring map presents the keywords in color code depending on the clusters of the entities; five groups were detected in this network. The yellow set is the first group to review where the keyword "BIM" is mentioned in multiple nodes, and "architectural design" escorts them. BIM is an acronym for "building information modeling" software, which is a tool heavily used in construction in the last few years because of its smart features, such as 3D modeling, cloud storage, information sharing, and others [35,83]. In the green cluster, topics related to data analysis are gathered, and those such as "smart manufacturing", "cyber-physical system", "machine learning", and "artificial intelligence" cover the main topic. Curiously, the keyword "robotics" is placed in this cluster. However, it is positioned right next to the blue group, which covers issues related to the manufacturing industry such as "automation", "industrial research", "3D printing", and "manufacture". A brief look at the map allows realizing that the "manufacture" node emerges from the "industry 4.0" node, and the two topics "robotics" and "automation" bifurcate from it. Figure 14 displays the time-based network in addition to the co-occurrence map, where the color code represents the latest developed nodes in yellow and the oldest topics in purple. It is worth mentioning that even the oldest keyword in this figure is from 2019, meaning that its relevance still prevails. "Digital twin", "artificial intelligence", "blockchain", and "Construction 4.0" are the leads in the most recent keywords, and represent the latest interest of researchers as well as showing how the definition of Construction 4.0 is still in its development. On the other hand, "3D printers", "manufacturing industries", and "office buildings" are the oldest keywords from this map or the first topics authors considered worthy of investigation in this field.

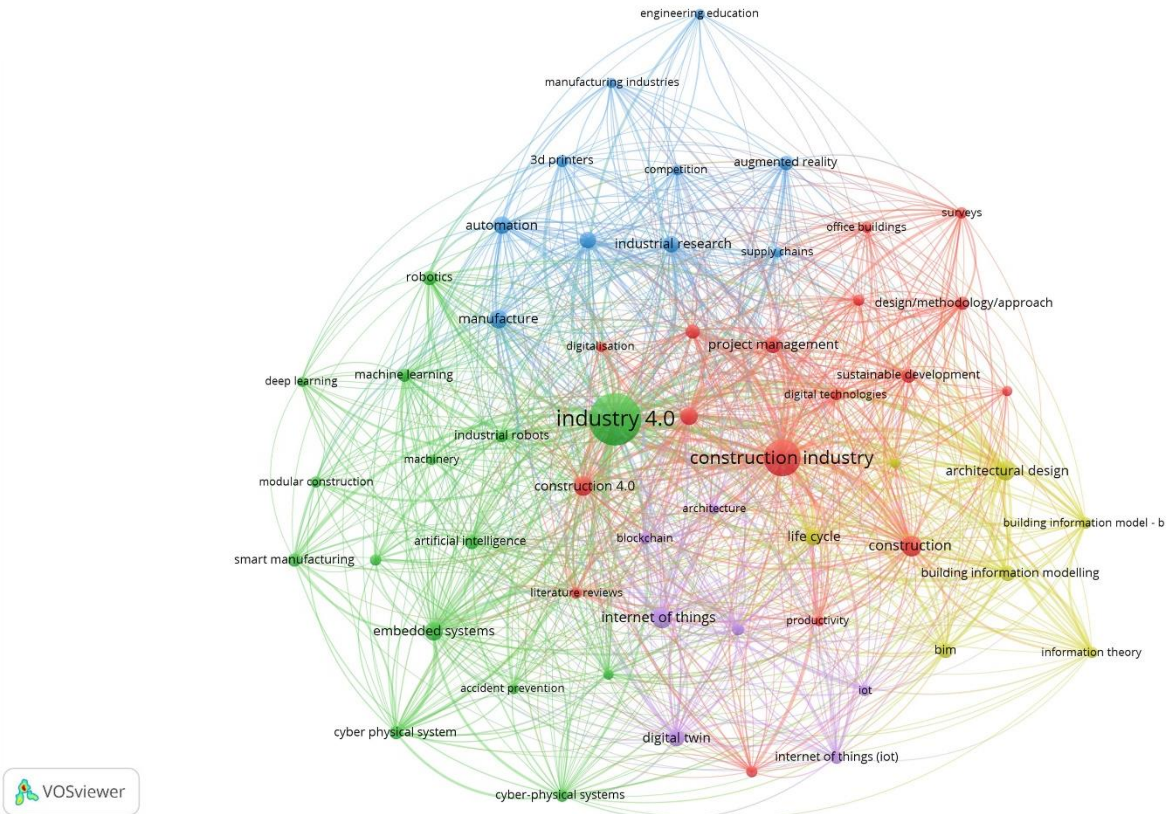

Figure 13. Network map of co-occurring keywords for Industry 4.0 in construction (2006–2022).

Table 8. List of selected keywords and relevant network data for Industry 4.0 in construction.

Keyword	Occurrences	Average Year Published	Links	Total Link Strength
Industry 4.0	322	2020	55	839
Construction industry	157	2019	54	535
Internet of things	52	2020	47	197
Architectural design	48	2020	49	254
Embedded systems	42	2020	51	200
Manufacture	39	2019	41	124
Industrial revolutions	38	2020	45	166
Automation	37	2019	46	122
Life cycle	33	2019	44	143

Table 8. *Cont.*

Keyword	Occurrences	Average Year Published	Links	Total Link Strength
Decision making	32	2020	41	109
Digital twin	31	2021	44	131
Industrial research	31	2020	45	128
Project management	31	2020	39	115
Building information modeling	29	2020	39	122
Artificial intelligence	27	2020	40	102
Robotics	27	2020	36	105
BIM	26	2020	32	94
Augmented reality	25	2020	34	72
Sustainable development	24	2020	41	100
Machine learning	23	2020	35	79
Design/methodology/approach	22	2021	38	108
Smart manufacturing	22	2020	27	64

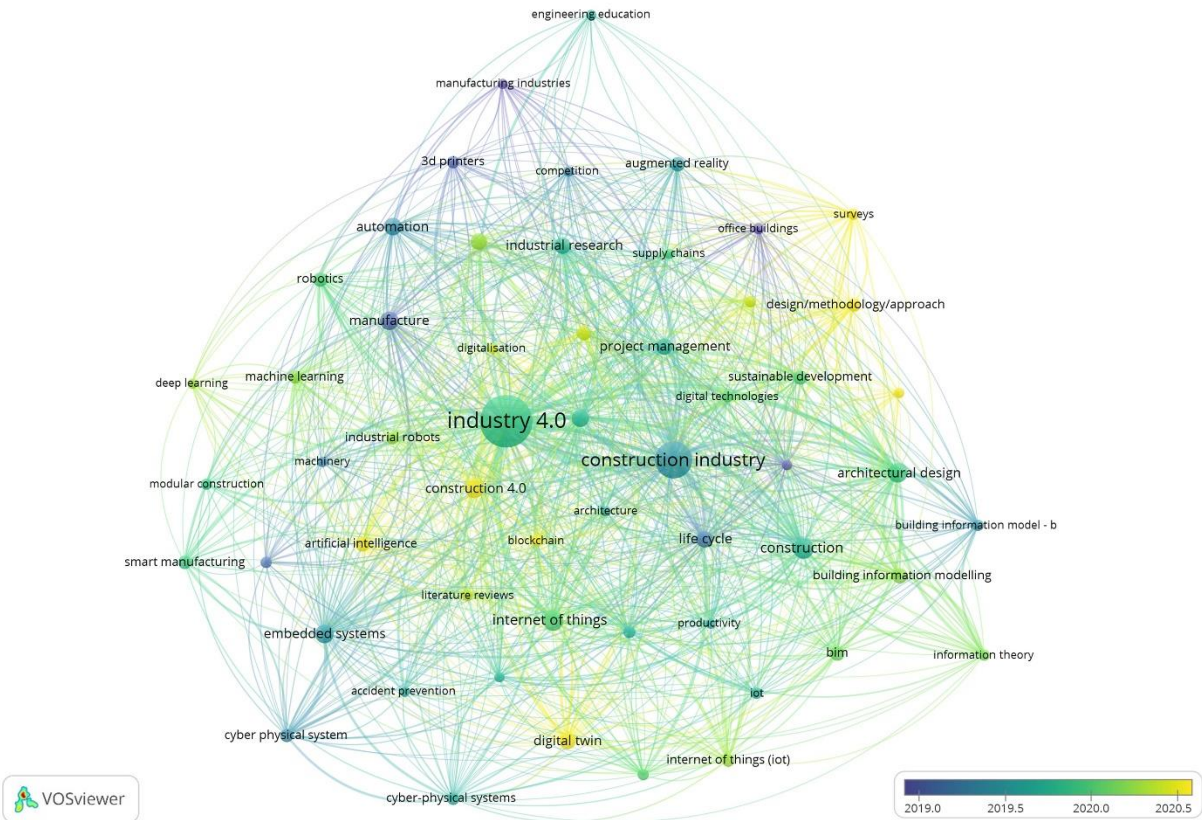

Figure 14. Time-based network map of co-occurring keywords showing the development of nodes based on the average year for Industry 4.0 in construction.

4.3. CiteSpace Network Maps

The scientometric analysis for understanding the trending knowledge for Industry 4.0 in construction was performed more lightly than that in the previous section. Because of the vast amount of topics Industry 4.0 could cover, performing extensive research in this area would push the study out of the scope of this article. What is intended in this study is to find trends and research gaps in the intersection between cross-laminated timber, Industry 4.0, and the construction industry. Therefore, not all network maps were implemented, and some even provided negligible information. For example, contrary to the CLT analysis, the co-authorship network map for Industry 4.0 is not suitable for this study because the result given by CiteSpace shows a scattered network where it is hard to find nodes and connections. These results suggest that only certain authors have worked together in publications, highlighting an opportunity for the academic community in this field. From the small list obtained, the first author is Dominik T. Matt [84] with seven documents, and the second author is Patrick Dallasega [85] with five publications. Both researchers belong to the Free University of Bozen Bolzano in Italy.

A journal co-citation network was created to determine the journals with more importance related to Industry 4.0 and construction. CiteSpace generated a network map with enough homogeneous balance on all the nodes, but the critical information is present in the cited journal list. In this list, the leading cited journals are as follows: *Automation in Construction* (count of 96 and centrality of 0.12), *Procedia CIRP* (count of 61 and centrality of 0.08), *Applied Sciences* (Switzerland) (count of 33 and centrality of 0.09), *Buildings* (count of 26 and centrality of 0.0), and *IEEE Access* (count of 23 and centrality of 0.03). From this list, a burst analysis was generated, where the entity with higher strength is *Procedia CIRP* with 4.51 between 2017 and 2018, followed by *Applied Sciences* (Switzerland) with a burst strength of 3.36 from 2018 to 2019. The rest of the journals did not present a considerable strength, but it is worth mentioning that the remainder of the list has a presence after 2016. Additionally, the centrality was calculated for all the documents. All the results came with values below 0.15, meaning that there is still no journal or conference that is central to the research in this field.

A network map created was for countries or regions, as seen in Figure 15. This map has 18 nodes and 174 links. The five leading countries with publications on Industry 4.0 in construction are as follows: the United States has the first position with 52 documents, and its top authors are Bing Qui from the University of Florida and Konstantinos Mykoniatis from Auburn University; the second leader is Italy with 39 publications, where Gabriele Pasetti Monizza from Free University of Bozen-Bolzano and Fabio Bianconi from University of Perugia are the top authors; the third position is taken by Germany with 38 publications, where Viktor Mechtcherine from Technische Universität Dresden and Xi Chen from Fraunhofer Institute for Manufacturing Engineering and Automation are the lead authors; the fourth place is for China with 33 documents, where the leading researchers are Keliang Zhou from Wuhan University of Technology and Heping Xie from Shenzhen University; and the fifth position is taken by Malaysia with 29 publications, where Wesam Salah Alaloul from University Technology PETRONAS and Raihan Maskuriy from Malaysia Japan International Institute of Technology are the leading researchers. In terms of centrality, the United Stated has an outstanding record of 0.55, positioning this nation as a central entity for Industry 4.0 in construction. Unsurprisingly, "USA" is the only node in the center of the map with the purple outer ring to highlight its centrality. Contrary to this position is Germany; even though it has a high number of publications in this field, its node is isolated and aside from the main body of nodes in the network. This suggests that the German academic society should collaborate with other countries.

In addition, a co-citation network map was created for the authors working on topics related to Industry 4.0 in construction. This network intends to detect the most influential researchers in the field. The map is presented in Figure 16 and has 458 nodes and 1764 links. The leading authors from the network are as follows: the first position is taken by Thuy Duong Oesterreich from Osnabrück University with 40 citations; the second position is for Patrick Dallasega from the Free University of Bolzano with 37 citations; in the third position, Jay Lee from the University of Cincinnati with 34 citations; Henning Kagermann takes the fourth position with 28 citations; and Xiao Li from The Hong Kong Polytechnic University takes the fifth place with 25 citations. The author diversity shows how broad the research on Industry 4.0 in construction has been. Additionally, the centrality was calculated for all the nodes, but none had a score above 0.2, meaning that there is no author central for this field yet. Similarly, no author has shown enough strength or length in the citation burst, and the only worthy note is that all of them started to appear in the table after 2017.

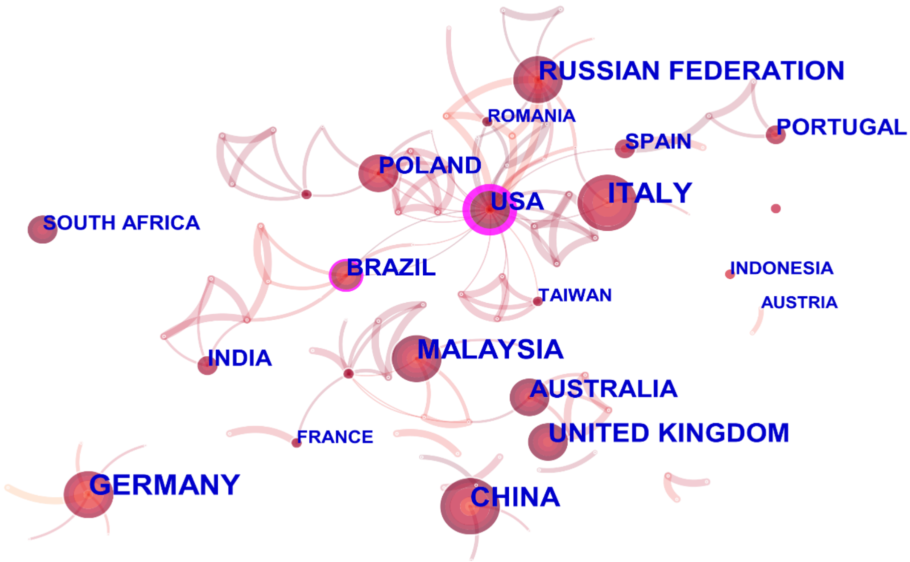

Figure 15. Network of countries/regions for publication of Industry 4.0 in construction from 2006 to 2022.

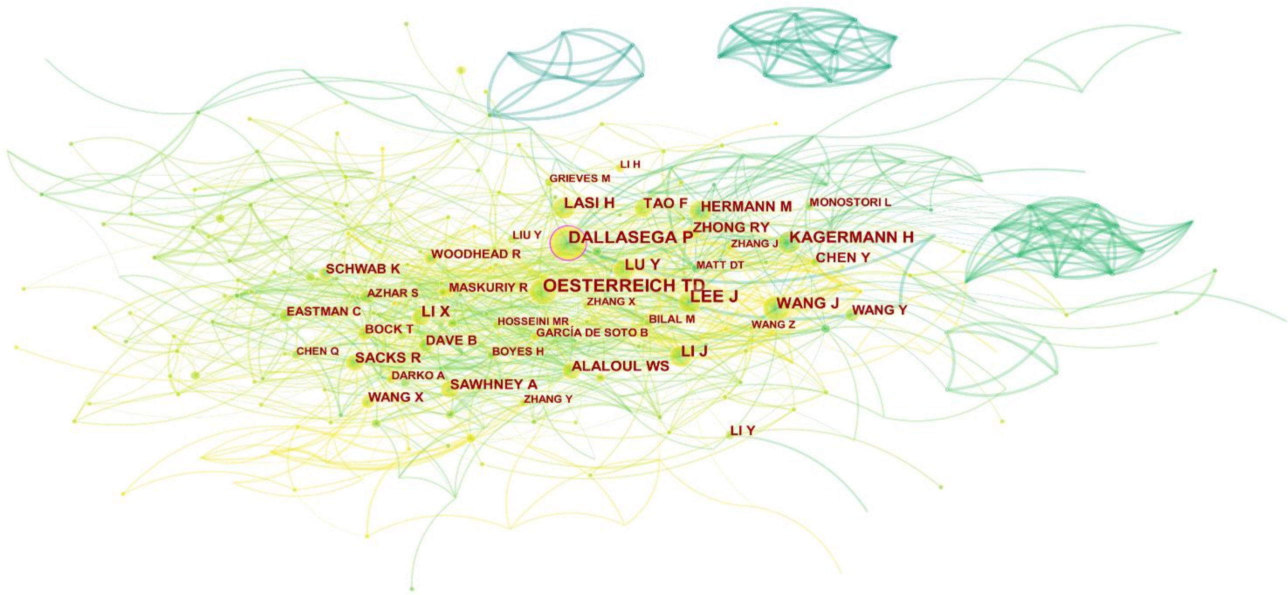

Figure 16. Author co-citation network for publications related to Industry 4.0 in construction.

The final network map is the document co-citation network displayed in Figure 17. This map has 350 nodes, 830 links, and 5 clusters generated with the abstract terms of the publications. The network for Industry 4.0 in construction appears more scattered than that in the previous analysis, and even the number of clusters is around half of the preceding result. Only the top four authors surpass 10 citations. The first leading author is Patrick Dallasega (frequency of 22), who performed a schematic literature review looking to improve the construction supply chain with the concept of proximity [86]; the second author is Thuy Duong Oesterreich (frequency of 21), who performed a literature review for the state of digitalization and automation in construction [87]; the third place is taken by Anil Sawhney (frequency of 11), who published a book for the framework of Industry 4.0 in construction [88]; and finally, Roy Woodhead (frequency of 10) takes the fourth place with a literature review of IoT (Internet of Things) systems in construction [89]. Like the previous networks for Industry 4.0 in construction, the centrality of the nodes for the co-citation map is negligible. There was no cited document with a burst of more than two years or with enough strength.

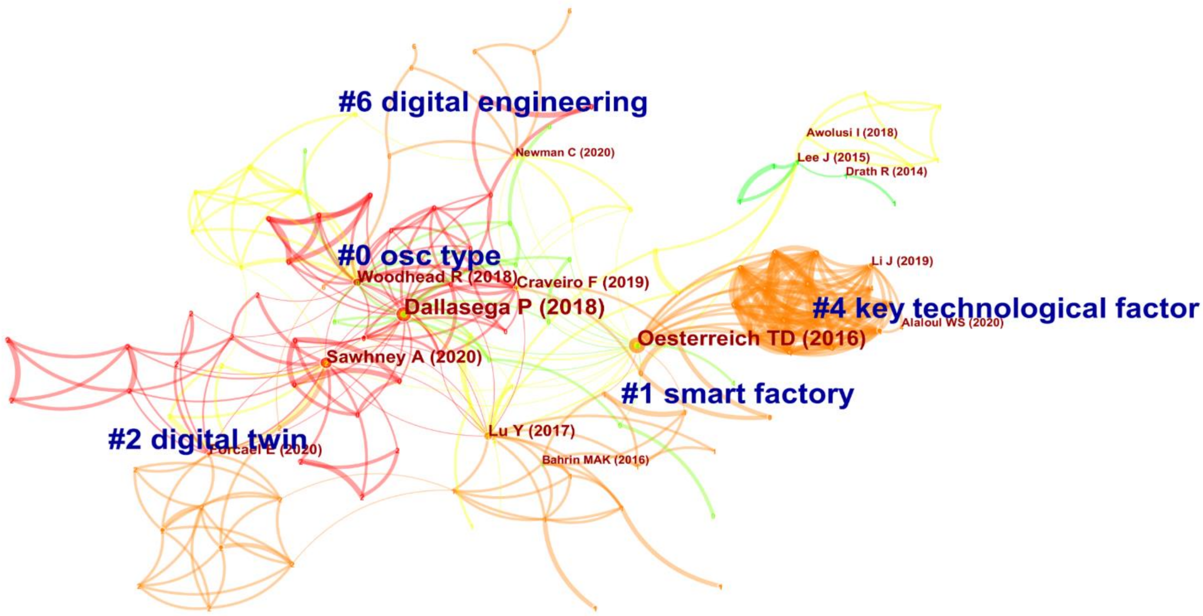

Figure 17. Abstract clustering network map of co-citations for Industry 4.0 in construction.

Clusters were generated in the co-citation network using the abstract term, and the results of the five elements are presented in Table 9. The largest group, #0, covers literature reviews on the state of Industry 4.0 in the construction field. Curiously, the more representative authors are Dallasega and Woodhead, who were at the top of the co-citation network. This cluster covers all kinds of reviews for different trending topics in Industry 4.0, for instance, IoT, digital twins, cyber-physical systems, and smart factories. Nevertheless, the publications found in this cluster do not investigate the topic profoundly, and they only seek to understand the current advances in construction. The second cluster, #1, is named "smart factory", and the alternative label is "case study". In this cluster, it is possible to find publications on case studies related to "smart" factories or manufacturing; an example is the work of Al-Seed, where digital objects were used in building information modeling (BIM) to simulate the automation of manufacturers in the construction industry [90]. Another instance is the work of Li, who used RFID and BIM technology and improved the schedule performance of prefabricated house construction (PHC) [91]. In the third cluster, #2, the topic covered is "digital twin", where the documents gathered cover multiple issues related to this technology. Yet, it is essential to mention that numerous publications mention BIM as one of the critical tools in digitalization and digital twin development for construction. Here it is possible to find studies such as that of Shirowzhan et al., who studied the BIM applications and their compatibility in the construction industry and multiple levels of typical companies [92]. The fourth cluster, #4, is dedicated to publications researching data usage in construction. Some authors suggest the introduction of blockchain to improve the supply chain, while others consider the use of big data for decision-making. Lastly, the fifth cluster, #6, gathers publications related to the digitalization of different areas in construction, where BIM is mentioned again. For instance, Bortolini et al. made use of BIM to improve the logistics planning and control for customized prefabricated buildings [93].

Table 9. Co-citation clusters of Industry 4.0 in construction from 2006 to 2022.

Cluster ID	Size	Abstract Cluster Label	Alternative Labels	Mean Publication Year	Representative Documents
#0	40	OSC type	Literature review	2018	Dallasega [86], Woodhead [89]
#1	29	Smart factory	Case study	2016	Al-Saeed [90], Li [91]
#2	25	Digital twin	BIM	2018	Shirowzhan [92], Busswell [94]
#4	18	Key technological factor	Blockchain/information sharing	2018	Li [95]
#6	10	Digital engineering	Digitalization/prefabrication	2018	Bortolini [94]

5. Future Trends

5.1. Overview

This article makes use of scientometric analysis to review the current work in the fields of cross-laminated timber and Industry 4.0 in construction. The investigation was performed in two separate sections, first covering CLT in construction and then reviewing Industry 4.0 in construction. The aim was to find the intersection among the three topics and detect possible research gaps.

The first data given by Scopus clarify the attention attracted by cross-laminated timber in construction in the latest years, especially after 2015, when the IBC included CLT as a primary structural element. Following the trend from the academic publications, it is estimated that 169 documents will be published concerning this field by the end of the year. Following the color code for the keyword co-occurrence analysis in Figure 3, it is possible to say that researchers have focused on four groups, namely structural behavior, material properties, environmental impact, and sound isolation; structural behavior is by far the most substantial cluster, and multiple keywords are related, such as "structural design", "seismic design", and "finite element method". On the other hand, even though cross-laminated timber was initially developed in Europe, with origins in Austria and Germany, it is safe to say that North America (the United States and Canada) is genuinely involved in the research of this field. This note is made based on two facts. First, the leading seven most productive authors (Table 3) were led by researchers from these nations. Second, the USA and Canada have the bigger-sized nodes in the network map created for the countries (Figure 6), and their centrality score combined is superior to the rest of the nations. In the author co-citation network (Figure 8), it is possible to see that the scientists with the most collaboration are Thomas Tannert, Shiling Pei, and John W. van de Lindt, all from North America. As a complement to the note made in the keyword co-occurrence analysis, the journal co-citation network (Figure 10) states that the most prominent journals are those related to structural analysis and material properties, listing the top three journals as follows: *Construction and Building Materials*, *Engineering Structures*, and *Journal of Structural Engineering*. Additionally, in the document co-citation network (Table 5), the most cited publication was from Brandner et al., whose work is an overview of the material properties, suggested design, and connections of CLT. The high impact of their study is understandable because it was released in 2015, the year of the inflection point when CLT took relevance.

Furthermore, the clusters generated using the abstracts of the publications (Figure 11 and Table 6) indicate that the most critical field for CLT in construction has been structural behavior and mechanical properties. Considering the relevance this material has taken in North America, it is understandable how essential it was for the authors to comprehend the material for construction because the soil is completely different from the continent of origin. This is highlighted by cluster #0, which gathers over 50 publications studying the seismic characteristics of the material to understand its usage in seismic areas. Thus, with the data provided by the multiple network maps, it is feasible to state that the use of cross-laminated timber in construction has increased starting in 2015 as an effort by the researchers to reduce its carbon footprint and develop a sustainable industry. In contrast, North America has been the continent with more interest in its development, and its implementation started with short story buildings, but lately, it has been used for tall timber constructions. The effort of the authors to understand the mechanical properties of CLT has given results, and now it is possible to see construction projects such as the super-tall Oakwood Tower, which is looking to achieve 300 m of height [96]. On the other hand, it is apparent how dense the research effort in the structural analysis of CLT is, but at the same time, the lack of work in other areas of research is obvious. Finding a few publications on topics related to sustainability is conceivable, but the number of publications for topics such as manufacturing and automation is practically null. Therefore, a quick analysis of the field of Industry 4.0 and construction is needed to understand the knowledge network and its trends.

The data obtained from Scopus for Industry 4.0 in construction show an upward trend similar to cross-laminated timber, with a different inflection point, 2017. This timing is odd, and there was no event found as an obvious point of bifurcation, but it is interesting how close the year of inflection is for both research fields. Even though the fourth industrial revolution had a formal origin in 2011 in Germany, it took six years for authors to consider applying these features in the construction industry [97]. The first analysis tool in this study for Industry 4.0 was the keyword co-occurrence network map, which shows five groups of interest following the color code (see Figure 13). Here, the most significant green group covers keywords related to the data analysis, and the second cluster, in blue, covers those related to the manufacturing industry. Curiously, the keyword "robotics" is included in the data analysis cluster, but it is placed on the border next to the blue group. With a little more attention, it is possible to see how the "manufacture" node emerges from the Industry 4.0 main point, and "robotics" and "automation" rise from this keyword.

Additionally, it is worth noting the existence of a cluster focused on BIM software, used heavily in the construction industry. In the time-based network map (Figure 14), it can be seen how the latest topics are "digital twin", "artificial intelligence", and "Construction 4.0", giving a clue of the importance this field is taking in the construction industry. Sadly, the co-authorship network map barely shows a node with authors, meaning collaboration between researchers is needed. On the other hand, the journal most relevant to the field is *Automation in Construction*, which had a frequency of 96 publications in it; looking at the network map for countries (Figure 15), it is possible to list the leading nations in the field, where the United States takes the first position, followed by Italy in second, and the remaining leaders are Germany, China, and Malaysia. Here the United States stands outs against others in centrality with a score above 0.5. Thuy Duong Oesterreich is the author with more relevance in this field, and Patrick Dallasega takes the second position; see Figure 16 for the co-citation network. This map shows the high number of authors working in the field, but they are widely spread, meaning that there is still no single author who has taken extreme relevance. The last map used was the co-citation network in Figure 17, where a significant number of the documents were spread out and not connected with others. This display helps in understanding the trending topics of Industry 4.0 in construction. However, from the clusters generated using the abstracts, it is noticeable how the leading group is related to literature reviews. Here all the publications are seeking the possibility of Industry 4.0 features in construction, showing how researchers are highly interested in this field but at the same time presenting how immature the area is yet. The second cluster is related to case studies, and part of this group was expected as most of the time, each construction building is considered an individual project, and practically there is no mass production like in the manufacturing industry. The rest of the clusters are dedicated to digitalizing multiple areas, where BIM takes a relevant position among them, and there is even research interest in prefabrication techniques. From all the network maps and tools just presented, it is possible to conclude that Industry 4.0 has taken high relevance in the construction industry; however, research fields are still immature, and the authors' efforts are widely spread.

5.2. Future Trends

After the scrutiny of both fields, it was found that there are three trending areas from Industry 4.0 in construction, namely prefabrication, digital twin, and automation. Therefore, a deeper review of them will be performed in this section to understand the current status of these topics for cross-laminated timber. The search for publications was implemented in Scopus in three independent inquiries. The base keywords were typed as "cross-laminated timber*" and "construction", and the topic variation was included as "prefabrication*", "digital twin*", and "automation". In addition, the period was limited to the latest five years, from 2018 to 2022, and the subject area selected was engineering. Here it is worth noting that no document showed up in the inquiry for digital twin results, and the keyword was replaced by "digitalization" in an attempt to obtain a snapshot of the research close to this field. The number of publications obtained was 15 for digitalization, 21 for prefabrication, and 7 for automation. These small numbers reaffirm the immaturity of the research in this field.

The results found in Scopus for prefabrication or off-site construction represent the topic with the most documents, and they can be grouped into three subgroups, *mechanical behavior*, *comparative*, and *design*. There are studies about the mechanical behavior of the prefabricated sections of CLT and its performance in the entire building in the first group. Here Loss et al. analyzed the in-plane stiffness for hybrid CLT–steel floor panels [98]. Their methodology included a finite element analysis and validated the simulation with a case experiment. Mayencourt and Mueller performed a cost and material optimization of CLT panels used on floors, looking at the bending behavior [99]. Their work changed the core layers and achieved an 18% weight reduction without loss in performance. Another author working to understand CLT is Orlowski, who performed a study to validate design curves and strength reduction factors for post-tensioned timber–steel stiffened wall systems [100]. His article explains the finite element method used for the wall system and the experimental setup used for his validation. This work ends with design curves ready to be used to develop mid-rise buildings of hybrid timber–steel walls. Another subgroup for prefabrication is the publications focused on comparative studies. For instance, Ghafoor and Crawford compared different materials used in prefabricated residential walling systems in Australia to reach the lowest greenhouse gas emissions (GHG) [101]. The results showed that timber-framed panels were the only material that could lower GHG by 7% compared to conventional brick veneer construction. Surprisingly, structural insulated panels (SIPs) provided 6% more GHG than brick veneers. Østnor et al. are other researchers working in comparative studies, and their case study compares cross-laminated timber against on-site cast concrete [102]. Their work included a literature review and case study comparing different properties between two buildings, one with each material. They found that the CLT building had a 9.5% improvement in construction time, improved HSE, better dimensioning than concrete, and a 7% increase in the total cost. The authors comment that a high percentage could enhance the cost of CLT projects in the future as the current contractors have null or little knowledge of its use. The last group of documents in the prefabrication inquiry lay under the design field. Here it is possible to find case studies where the authors show the design process for their projects. For example, Bechert et al. explain the steps and methodology used to develop the Urbach Tower in Germany, a 14-meter-high building made of a single-curved shell structure [103]. The complex shape of this project was made of self-shaped CLT, using the natural shrinking of wood and the prefabrication technique.

The authors used an integrative design process to develop the tower, where the design, fabrication, and assembly were iterated to obtain the best result. Additionally, Jamnitzky and Deák described the process in the current development state of the Technical University of Munich (TUM) Campus in the Olympiapark in Germany [104]. This project is made of 80% wood, and the ceilings are made of CLT–concrete composite material. Part of the roof has 18.3 m of cantilever projection. All the CLT panels were prefabricated, and even the concrete composite parts used off-site panels but in-site concrete cast. Moreover, Gasparri and Aitchison developed a novel development design technique for CLT walls, including facades, with the help of a unitized timber envelope [105]. Their design allows them to prefabricate the walls, but in the installation process, there is no need to access facades from the outside to complete joints, reducing part of the construction time.

The publications obtained under the "digitalization" inquiry are far from the concept of the digital twin, which was the initial searching intention and is trending in the construction industry. The results are in completely separate fields where new technology is used, such as finite element analysis, computer-assisted design, and computer vision. One example of these studies is the work of Gamerro, whose work is dedicated to the development of digitally produced wood–wood connections for free-form structures [106]. On the other hand, Chen et al. reviewed the current state of piezoelectric sensors and actuators to understand the behavior of a building and its sustainability [106]. Another example is the work of Ahmadian Fard Fini et al., who used surveillance cameras to automatically track the installation speed in prefabricated CLT buildings [107]. However, although the work of these authors is highly valuable, it does not reach the desired research field, digital twin, or even cyber-physical systems. This only highlights the lack of work for digital twin examples in cross-laminated timber, despite digital twin being a trend in the construction industry.

There are two types of studies found in the publications obtained in the automation section. The first studies cover mass customization, a topic from Industry 4.0, in the design of buildings with cross-laminated timber. Bianconi et al. used generative algorithms and evolutionary principles to develop a web-based design space catalog for timber structures [81]. Their form-finding methodology aids in providing a visual representation considering the constraints and construction restrictions from the setup, helping developers to make better decisions on the final shape of the building. Similarly, Jalali Yazdi et al. used a genetic algorithm to study mass customization [108]. Yet, their approach looks for a cost optimization where their work considers the production process variables and provides the design with the lowest cost. The second topic is the usage of industrial robots in the manufacturing process of CLT projects. Joyce and Pelosi researched Japanese joinery techniques for the union on CLT panels [109]. Their case study used an ABB industrial robot because of the facility these robots have when handling complex movement. There are two other study cases, namely the one from Früh et al., who worked on a hybrid shell structure of CLT and concrete for the train station in Stuttgart [110], and the work of Gollwitzer et al., who made an abaxially curved shell for the synagogue in Regensburg [111]. Both cases had to use industrial robots because of the complex shapes of their design and for the convenience of the robots' six axes, which can easily handle these movements.

From the scientometric analysis and the deeper review of the trending topics, it is possible to see research gaps in the construction industry for cross-laminated timber. However, as explained at the beginning of the article, the intention is to find areas of opportunity for CLT manufacturing in the innovative path of Industry 4.0. Therefore, it can be said that there are two possible research gaps in the findings of this study. First, there is no study for developing a digital twin for the off-site manufacturing of cross-laminated panels with the usage of industrial robots. The digital twin is a trending area for construction, as shown in clusters from Table 9, but there are no articles found on any implementation for CLT; following the trending of automation from the deeper review, it is critical to consider industrial robots as they show an advantage when handling complex shapes. Second, once the digital twin is implemented, it is essential to automate its manufacturing process to help developers make decisions and reduce production time. Considering the work from Bianconi, automation is a critical feature for construction as it makes the industry more efficient and saves time for developers. Additionally, it will make no sense to develop an advanced digital twin for CLT and leave the programming manual.

6. Conclusions

Cross-laminated timber is a material that has gained attention in the last few years in the construction industry, and researchers and practitioners are interested in its application. A scientometric comparison study between research for this material in construction and Industry 4.0 was proposed to understand the current status and global trends for CLT. Although the study was conducted from a manufacturing perspective, the results obtained from both analyses are uncontaminated, and only at the end of the study can the manufacturing inclination be seen. Multiple literature reviews have already been attempted, yet this paper presents the first scientometric comparison study of the field as a whole, where 753 documents, in journals and conference proceedings, were considered for cross-laminated timber in construction and 567 documents were considered for Industry 4.0 in construction. The science mapping approach provided the key researchers and institutions, the condition of the research field, and important topics in both areas. From the CLT mapping, it was found that the authors have emphasized the structural behavior, properties, and environmental impact of the material. This result can be seen in different sections, and even the most populated journals are related to structural themes. On the other side, the mapping for Industry 4.0 in construction has given broader results, and it is possible to say that its development is still in the infancy stage. This was concluded from the clusters obtained in the co-citation network as the most populated group was "literature reviews", highlighting the interest researchers have in the topic. Aside from this cluster, there is a high interest in research themes such as digital twin, prefabrication, BIM, and automation. These clusters were subjected to a deeper inspection to understand the latest publications in the last five years for CLT. The issue to be highlighted is the lack of research on the "digital twin" for cross-laminated timber, even though this is an essential theme in construction. In prefabrication, called off-site by other authors, there are publications related to three areas, mechanical behavior, comparative studies, and design. On the other hand, in the automated section, it was found that most of the publications are divided into two subgroups, mass customization and industrial robots for manufacturing.

Regardless of the contributions found in this article, the discoveries should be considered in light of some limitations. As explained before, the findings are constrained by the selected keywords and the additional restriction set as input in the inquiry of the academic data; therefore, the scope of coverage for the existing literature is limited. Moreover, interrogating the reasons "why" and "how" of the academic publications used in this study is out of the scope of the objectives. Thus, even though research gaps have been identified, pursuing these areas of opportunity will be work for future research. In addition, it is essential to perform a similar analysis in the near future to observe the evolution of the research field and oversee its progress.

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