sustainability

MDPI

Article

Using Timber in Mid-Rise and Tall Buildings to Construct Our Cities: A Science Mapping Study

Alexander Wenzel [1], Pablo Guindos [1,2,3] and Manuel Carpio [1,3,4,*]

1 Centro Nacional de Excelencia para la Industria de la Madera (CENAMAD), Pontificia Universidad Católica de Chile, 4860 Vicuña Mackenna, Santiago 7820436, Chile; aawenzel@uc.cl (A.W.); pablo.guindos@udc.es (P.G.)
2 Department of Structural and Geotechnical Engineering, Pontificia Universidad Católica de Chile, 4860 Vicuña Mackenna, Santiago 7820436, Chile
3 Department of Construction Engineering and Management, Pontificia Universidad Católica de Chile, 4860 Vicuña Mackenna, Santiago 7820436, Chile
4 Department of Construction Engineering and Project Management, University of Granada, Campus Fuentenueva, 18071 Granada, Spain
* Correspondence: manuel.carpio@uc.cl or carpio@ugr.es

Abstract: The increase in population and urban migration has incentivized the construction of mid-rise and tall buildings. Despite the incremental rise in vertical construction, there are still investigation gaps related to high-rise buildings, such as carbon emissions and the use of low-carbon materials in tall structures. Timber presents a potential sustainable solution for mid-rise and tall buildings. The history of topics in timber building investigations began with the material characterization of innovation in construction technologies such as cross-laminated timber (CLT) and practical topics like construction collaboration, sustainability, engineering, and construction science. To identify potential topics and understand the research history of mid- and high-rise timber buildings, a bibliometric analysis is proposed. Therefore, this article aims to perform a bibliometric analysis with a science mapping technique to categorize and analyze the evolution of mid- and high-rise timber building research topics and identify the most relevant trends and current challenges. A co-occurrence keyword analysis was performed with the software SciMAT to analyze the evolution and actual trends of mid-rise and tall timber buildings. The results show an evolution in the investigation topics from timber frame elements to mass timber and CLT for high-rise buildings, which was expected due to the higher structural capacity of the mass timber product. Surprisingly, sustainability topics such as carbon emission and life-cycle analysis (LCA) were transversal in all periods with concrete as a recurrent keyword in the analysis. More specialized topics such as robustness, disproportioned collapse, perceptions, and attitude were observed in the final periods. Research projections indicate that for mid-rise and tall timber buildings, the environmental potential has to be aligned with the structural feasibility and perception of the construction's actors and society to improve the carbon emissions reduction and support the increment of the population in an urban context.

Keywords: bibliometric analysis; tall building; timber; multi-storey building; science mapping

check for updates

Academic Editor: Antonio Caggiano

Received: 16 December 2024
Revised: 12 February 2025
Accepted: 19 February 2025
Published: 24 February 2025

Citation: Wenzel, A.; Guindos, P.; Carpio, M. Using Timber in Mid-Rise and Tall Buildings to Construct Our Cities: A Science Mapping Study. *Sustainability* **2025**, *17*, 1928. https://doi.org/10.3390/su17051928

1. Introduction

An increase in population and migration trends from rural to urban contexts means an increase in the urban population influx and, considering the limitations of urban sprawl, vertical dimension should be taken into consideration [1]. For example, due to the expected increase in the population of China, the construction of high-rise buildings is a viable solution to accommodate the increase in population in an urban context [2]. Despite tall buildings being a potential solution to population increase, research on high-rise buildings displays potential gaps related to energy simulation, thermal and visual comfort, renewable energies, and carbon emission, specifically with regard to the reduction in embodied carbon with the use of low carbon materials [3].

Timber, as a biobased material, presents the capability to capture carbon, which can contribute to decreasing the total embodied carbon of mass timber buildings and obtain a reduced amount of emissions in contrast to concrete buildings [4]. Constructing our cities with timber that comes from sustainably managed forests has often been argued as the most promising solution to reducing the embodied carbon of the great mass of resources used in construction, both from a scientific perspective [5] and from the perspective of the authorities [6].

Mid-rise and tall buildings represent a promising solution for urban sprawl. In addition, the application of timber in the structures can potentially achieve low emissions. However, three decades prior, it would have been unthinkable that timber could be a feasible solution to construct our cities, due to the societal need for taller buildings. However, in the 2000s, new timber products and technologies became popular, such as cross-laminated timber (CLT) and other mass timber products, which cemented timber's reputation as a feasible construction material for mid- and even high-rise buildings [7]. Early studies in multi-storey timber buildings began with fundamental subjects and topics, such as the characterization of timber properties as a building material [8]; the refinement of the structural codes such as the wind-load provisions uniform building code [9]; and seismic behaviour under the application of damped resonant appendages [10]. However, today's interest and research in timber buildings is greatly focused on critical aspects such as sustainability, engineering, construction science, and collaborative design [11]. To identify the potential topics, a clear comprehension of the research history of mid- and high-rise timber building lines of research is needed. Due to the large amount of data related to multi-storey tall timber buildings, research analytical methods such as bibliometric analysis can be used [12].

Bibliometrics analysis originated as a scientific computer-assisted review methodology that covers all the publications related to a given topic or field and can identify core research authors and their relationships [13]. Bibliometric analysis can be classified into two techniques: performance analysis and science mapping. Performance analysis focuses on contributions, while science mapping engages the relations between research variables [12]. A few bibliometric analyses on timber or wood have recently been made [14–17] mostly focused on specific structural components, materials, or forest level.

The increase in population and the necessity to develop low-emission solutions have propelled the use of timber as a building solution. Different topics in the research history of mid- and high-rise timber building research lines have evolved and emerged.

To address these issues, this study is structured around the following research questions: (1) What have been the main research lines in mid- and high-rise timber buildings over time? (2) What are the current research trends in this field? (3) What challenges and opportunities arise from implementing timber-based solutions in urban contexts? These questions guide our bibliometric analysis to provide clarity on the evolution of knowledge in this discipline.

Therefore, this article aimed to perform a bibliometric analysis with a science mapping technique to categorize and analyze the evolution of mid- and high-rise timber buildings research topics and identify the most relevant trends and current challenges. This is expected to be a relevant contribution in this incipient research field, for both established and new researchers to understand how the appearance of mid-rise and tall timber buildings is shaping the needs and trends of the entire discipline. The manuscript is organized as follows: the methodology section explains the theoretical elements, inputs, and outputs of the science-mapping analysis; the results section presents findings categorized by science mapping outputs and research periods; and finally, the conclusions summarize key insights and final reflections on mid-rise and tall timber buildings.

2. Materials and Methods

2.1. Setting the Analysis Database

2.1.1. Collecting the Publications of Mid-Rise and Tall Timber Buildings

According to Donthu et al. [12], the first step required to perform a bibliometric analysis is establishing the aim and the scope of the analysis. This bibliometric study aims to analyze retrospectively the evolution of research topics related to mid-rise and tall timber buildings and identify the actual research challenges. A flowchart of the bibliometric analysis is presented in Figure 1.

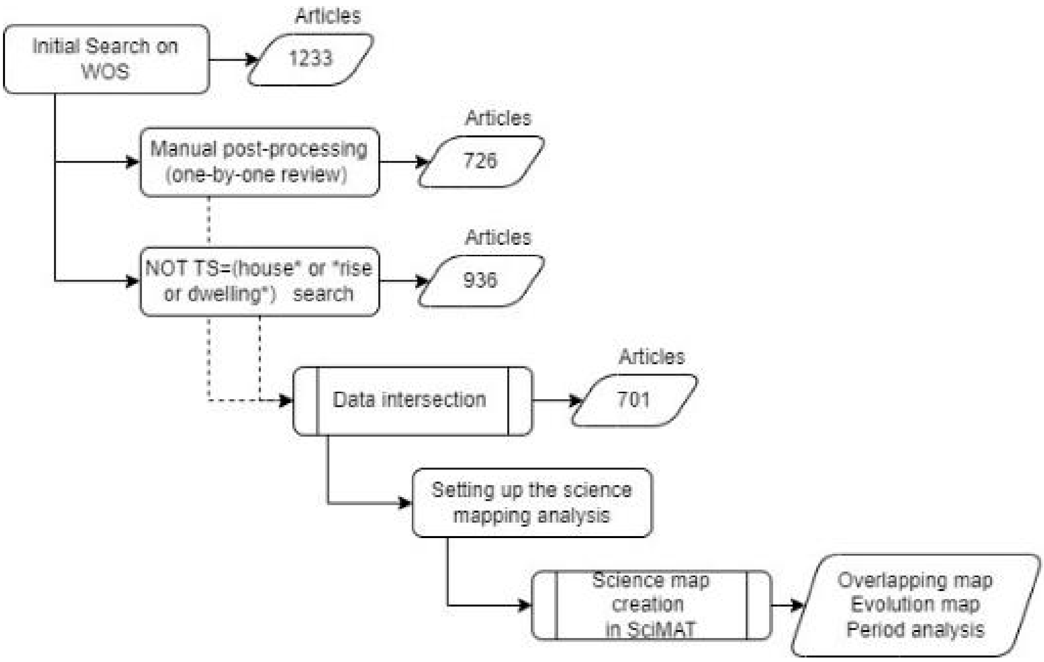

Figure 1. Flowchart of the bibliometric analysis from the data acquisition to the mapping and period analysis. (*) truncation operator that allows for the retrieval of different word variations by replacing multiple characters.

The bibliometric analysis was limited to the Web of Science (WOS) database due to the large number of articles, avoiding highly possible duplicated files, and using only one standardized file format [12]. Additionally, WOS possesses several citation and publication data for well-founded discovery and bibliometric analyses, exhibits a large collection of scientific publications and highly rated journals, and features a notable multidisciplinary nature useful to collect State-of-the-Art information [18].

The search was performed with no year restriction, but the final data obtained were until the end of 2022. The search formula used in this investigation is described in Equation (1). The format of Equation (1) can be used in the advanced search on the WOS database.

$$TS = ((timber^* \text{ or } wood^*) \text{ and } (building^*) \text{ and } (\text{"mid" or "tall" or "high" or "multi-story" or "multi story" or "multi-storey"})) \text{ and } (AK = (building^*) \text{ or } TI = (building^*)) \quad (1)$$

The term selection was chosen to cover timber or wood buildings with the additional characteristic of being mid-rise or tall height. The addition of the AND of building in the title or keyword was selected to filter non-related topics such as *microbiology* and *marine freshwater biology*, for example.

*F*0 represents the initial data set of articles matching with the above search criterion, which in this case consisted of a total of 1233 articles. The search criterion was conducted in the abstract, title, keyword, and keyword plus with an additional filter on the keywords and title, which consisted of a constraint related to the word building presented in the keyword or title. All resulting articles were selected at this first instance.

After the standardized search, a manual post-processing (one-by-one review) of the data was made. The data resulting from the manual review was called *F*1 and consisted of 726 articles. This manual filtering aimed to check the contents of the articles and avoid themes not focused on mid- and high-rise timber buildings. For example, it was discarded if wood was used as fuel for building climatization. Another criterion applied to the search was to reject articles focused on the forestry level or previous processes of a timber building. In the case of window frames or louvres articles, they were not selected if the wall was made using a building material other than timber. On the other hand, elements like floors, walls, roofs, or envelopes related to timber elements applied in mid- and high-rise buildings were selected. Investigations based on timber products but without an application on timber mid- and high-rise buildings were also discarded. In the case of timber-based articles that did not mention the case of the study, the investigation's scalability was reviewed to search for the potential applicability of mid- and high-rise buildings.

In parallel to the manual post-processing, the original search formula was modified to apply an additional constraint related to low-height buildings, low-rise buildings, houses, and dwellings. The filter comprised an exclusion formula, *NOT TS = (house* or *rise or dwelling*) and* the data set obtained was called *F*2. The modified formula found a total of 936 articles instead of the 1.233 of the first search.

A data intersection was then performed between *F*1 and *F*2. The objectives of this search were twofold: first, to check the accuracy of the manual filter results *F*1 concerning the more specific formula *F*2, reviewing the excluded articles in *F1* but added in *F*2. If the article was rejected in the *F*1 manual filter but added to *F*2, this could be an error in the manual filter, so the intersection allowed for a double check of articles manually discarded for reasons other than not being low-rise construction.

The second objective was to check the cases where an article was added to *F*1 but not to *F*2; this allowed us to double-check if, after manual filtering, any low-rise research was mistakenly included in the analysis. Figure 2 shows the different data filters applied and how they intersected with the number of resultant articles.

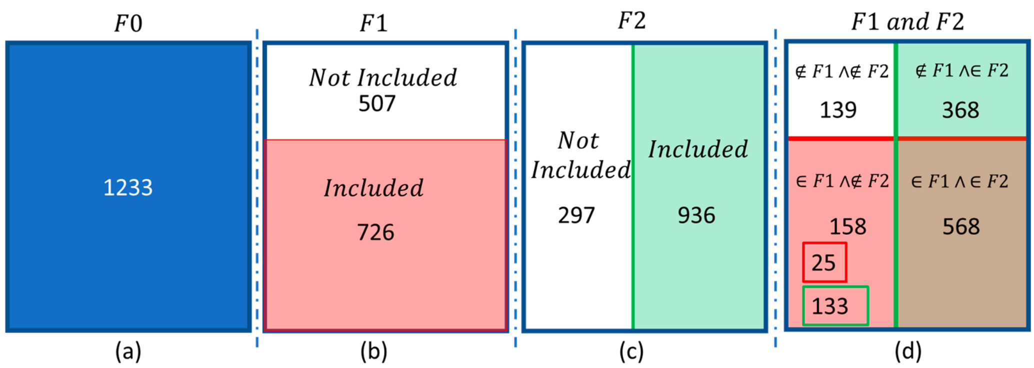

Figure 2. Research database acquisition, including the initial data set F0 (**a**), the manual filtering data set F1 (**b**), the low rise excluded filter data set F2 (**c**), and the intersections of F1 and F2 (**d**).

Regarding the first objective, by the intersection, it was found that 368 articles were excluded in *F*1 but added to *F*2. After manually reviewing the articles again, it was found that the *F*1 manual filter was correctly applied. Regarding the second objective, the number of articles included in *F*1 but not in *F*2 were 158, which were manually reviewed. Of these 158, 25 articles agreed that the focus was low-height, low-rise; houses and dwellings, therefore, were discarded. However, the remaining 133 articles were correctly added in *F*1 because the contributions could still be of relevance for tall timber construction. This resulted in a final database analysis set of 701 articles, 568 articles belonging to both manual filtering *F*1 and *F*2, plus the 133 articles that belong to *F*1 but not *F*2 and that were deemed as relevant for the investigation. The final data set resulted in the 568 articles belonging to *F*1 and *F*2, plus the 133 articles that belong to *F*1 but not *F*2 and were deemed as relevant.

2.1.2. Enriching the Analysis Database with KeyWord Plus

The tool KeyWord Plus of WoS permits the consideration of terms cited in references that do not appear in the authors' keywords of the article itself, thus, allowing for an enriched search and analysis due to multiple keywords derived from the metadata. However, the accuracy of the autogenerated words cannot always be precise. In this article, an additional review of the final 701 documents was performed, in which only 420 presented added words from KeyWord Plus. The additional review was made to ensure the added words' relationship to the articles' topics and contents. For example, in multiple articles, the word *green house gas* (*GHG*) was added to the KeyWord Plus category because several articles started their introduction to research problems by introducing the positive impact of timber in the reduction in GHG emissions [19,20]. Another example of misleading by KeyWord Plus was the use of the term *cyclic analysis*, which was added in a structural article referring to laboratory tests of elements under cyclic load [21]. The article presented a methodology to determine the technical feasibility of timber frame structures at early design phases for highly seismic zones but did not perform or analyze cyclic loads in any timber element.

In other cases, the addition of the KeyWord Plus was very accurate and gave more information about the article. For example, the investigation of Lazzarini et al. [22] analyzed and discussed the structural dynamics of high-rise timber structures, specifically the constructed Mjøstårnet in Brumunddal (Norway). Their keywords mentioned high-rise timber buildings and tall timber structures, but there was no information about the specific construction method. In this case, KeyWord Plus integrated the word CLT, giving a more detailed word that can be related later in the analyses.

After the review, it was observed that words like *performance*, *behaviour*, *system*, *design*, and *model* were added multiple times by KeyWord Plus. Due to the general nature of these words, their relationship with mid- and high-rise timber building articles was mostly correct. Despite the general characteristics of these particular keywords, the consistency of the extra information addition was not precise, leaving articles that presented topics of *performance*, *design*, and *model* without these additional keywords.

2.2. Setting Up the Science Mapping Analysis

2.2.1. Definition of Stages and Inputs

Bibliometric analysis can be performed through a performance analysis and a science mapping analysis. Science mapping analyses the relations among these indicators through different methods, delimiting research areas and monitoring a science field to determine the cognitive structure and its evolutions [23]. A co-word analysis over a science mapping tool was made to investigate the evolution and future research themes of mid-rise and tall timber buildings. The software SciMAT [24] was selected to perform the bibliometric analysis. As mentioned in [25], SciMAT was widely applied in psychology, marketing, computer science, and management. After the database was prepared, a four-stage process began in SciMAT: (i) the building of the data set; (ii) the network's normalization; (iii) the cluster algorithm selection to map the results; and (iv) analysis selection to be performed on the generated map. The sub-process of each stage is presented in Table 1, with their respective inputs used in the article.

Table 1. Stage, sub-process, and inputs for SciMAT.

Stage	Sub-Process	Input
1	Select periods	1988–2010 2011–2016 2017–2020 2021–2022
2	Select the unit of analysis	Words
	Data reduction per period	2 3 3 3
	Network base	Co-occurrence
	Network reduction	0 2 2 2
	Similarity measure for network normalization	Equivalence index
3	Cluster algorithm	Clustering algorithm: Simple centre algorithm Max: 9 Min: 5
4	Document mapper	Core mapper Union mapper
	Quality measures	H-index Sum citations
	Longitudinal and temporal analysis	Evolution map: Inclusion index Overlapping map: Jaccard index

The selection of the study periods (1988–2010, 2011–2016, 2017–2020, and 2021–2022) was based on significant milestones in the evolution of mid- and high-rise timber building research. The first period (1988–2010) represents the foundational stage, where research primarily focused on timber-frame structures and life-cycle analysis. The second period (2011–2016) marks the emergence of mass timber products, such as CLT, and the initial structural feasibility studies of mid-rise timber buildings. The third period (2017–2020) reflects a rapid increase in scientific publications, a shift toward robustness and collapse prevention studies, and growing interest in the environmental and societal perceptions of timber buildings. Finally, the fourth period (2021–2022) covers the most recent research trends, including hybrid structural systems, refined life-cycle assessment (LCA) methodologies, and advanced structural modelling for taller timber buildings. These divisions were established to capture major research transitions and allow a more detailed analysis of evolving themes within the field.

2.2.2. Normalization Measures

In science mapping, normalization measures are required to detect the interaction between the functional unit and the significant elements, such as keywords, clusters, or periods. SciMAT has three instances to select normalization measures: the cluster network, overlapping map, and evolution map. According to [26] in the co-occurrence analysis, the most appropriated normalization measure was the equivalence index from Callon, shown in Equation (2). In this example, c_i and c_j represent a value associated with the elements *i* and *j*, respectively. On the other hand, c_{ij} represents a value shared by the elements *i* and *j*. For example, if we assume that *i* and *j* are keywords, c_{ij} can be the number of documents that present them, with c_i and c_j being the number of documents presented with the keywords *i* and *j*, respectively [23,27]

$$E_{i\,j} = \frac{(C_{i\,j})^2}{C_i * C_j} \tag{2}$$

For the overlapping and evolution maps, the Jaccard indexes and the inclusion indexes were used, respectively, as shown in Equations (3) and (4). Their selection was based on the increase in the edge thickness of the connection to identify more clearly the relationship between clusters [28,29].

$$E_{i\,j} = \frac{C_{i\,j}}{C_i + C_j - C_{i\,j}} \tag{3}$$

$$E_{i\,j} = \frac{C_{i\,j}}{\min(C_i; C_j)} \tag{4}$$

SciMAT applies these normalization measures in conjunction with advanced statistical principles to enhance the accuracy and interpretability of science mapping analyses. The software employs co-occurrence techniques (e.g., co-word analysis, co-citation, bibliographic coupling) to construct relational networks, which are further processed using clustering algorithms and centrality-density metrics to identify key thematic structures. Additionally, SciMAT integrates evolutionary analysis methods, such as overlapping and transition indices, to track thematic persistence and transformation across time periods. To refine data interpretation, descriptive statistics are used to quantify term frequencies and distribution patterns, while impact metrics like the h-index and citation counts provide insight into the influence of research topics. Furthermore, SciMAT leverages dimensionality reduction techniques, such as correspondence analysis, alongside linguistic normalization, ensuring a structured and coherent representation of bibliometric data.

2.3. Science Mapping Outputs

2.3.1. Overlapping Map

The overlapping map is a graphic representation of the unit of analysis evolution trough periods [23], see Figure 3. In this investigation, the horizontal arrow between periods (X1) represents the keywords that are maintained from one period to the next. The element in the parenthesis (Y1) on the horizontal arrow represents the value of the normalization measure used in the analysis, in this case, the Jaccard index. The periods were represented by A1 and A2.

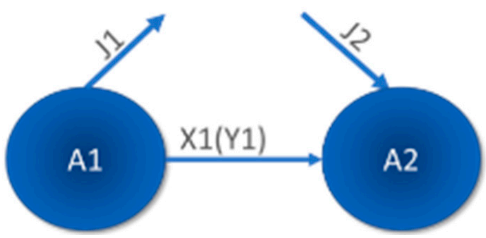

Figure 3. Theoretical overlapping map.

The arrow leaving the period in a cartesian Y positive direction (J1) represents the new keywords from the old period but are not included in the new period. The arrow entering the new period with a Y negative direction (J2) represents the new keywords integrated into the period.

2.3.2. Evolution Map

The evolution map shown in Figure 4 represents the theme development through the selected periods [30] in which the diameter represents the number of documents associated with the principal cluster.

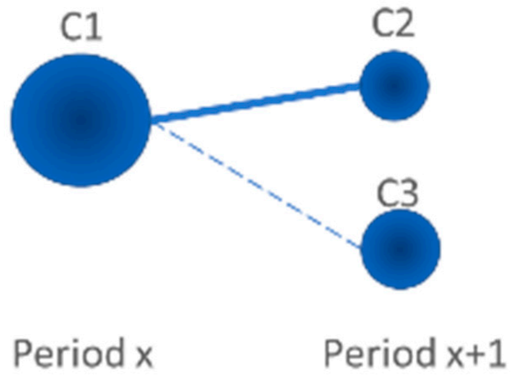

Figure 4. Theoretical evolution map.

In this research, the solid lines represent the fact that the cluster shares the main keyword with one of the clusters between periods. Conversely, the dotted line represents a connection between clusters (C1, C2, C3) with a keyword that is not the main one. The thickness of the line is proportional to the inclusion index, selected as a measure in the SciMAT interface.

2.3.3. Strategic Diagram

The strategic diagram is a graphic representation in a cartesian plane of the period's main clusters distribution. The placement is based on two variables, centrality (x-axis) and density (y-axis). Centrality represents the interaction degree of a single network with other networks and illustrates the external ties strength to other themes [23]. Density measures the strength of the internal ties among the unit of analysis, and it can be understood as a measure of topic development [23]. With the values of centrality and density, the cluster network can be classified in one of the fourth quadrants of the strategic diagram. The first quadrant is the motor theme, which presents a positive density and centrality and illustrates the cluster with the important topics in the research fields and their high development [31]. The second quadrant in a cartesian plane represents the highly developed but unconnected topics, mostly specific research topics. The third quadrant is the emerging or disappearing topics, with a low centrality and density. Finally, the fourth quadrant is the transversal and basic topics, which are topics not highly developed but important for the research fields [31]. The diameter of the cluster circle represents an indicator in the analysis. In this article, the diameter represents the number of documents per cluster network or cluster. Figure 5 shows the cartesian plane of the strategic diagram.

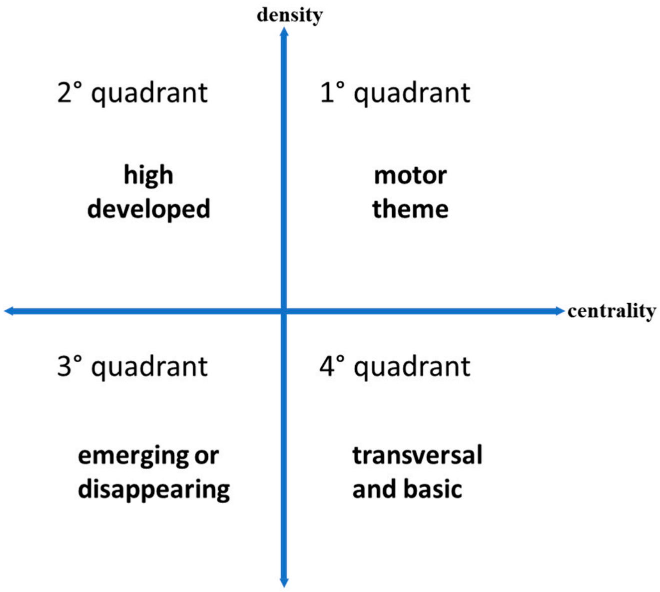

Figure 5. Theoretical strategic diagram.

2.3.4. Cluster Network

The cluster network represents the interaction between clusters that share a common unit of analysis. The name of the cluster network is represented by the most central unit of analysis [23]. The thickness of the edge represents the connection between two clusters and in this investigation, the edge thickness value corresponds to the equivalence index. As mentioned, the diameter of the circle represents the number of documents per cluster.

3. Results

3.1. Overlapping Map

In this investigation, the overlapping map reveals an increment in the number of keywords that are kept from one period to the following, from 55 to 282. The final period contains a reduced number of years for two main reasons: due to the increment of articles in the field and to identify current trends. Similarities in the cluster and periods are computed based on indexes or measures. In the case of the Jaccard index, shown between parenthesis in Figure 6, an increase through the periods was noticed. This increment indicates a potential common research topic in the past and future periods. Y positive and Y negative direction arrows show an increment of non-included and new keywords, showing high renovations on the investigation topics or keywords used.

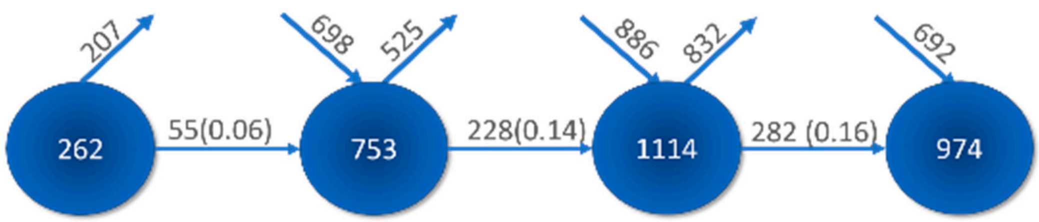

Figure 6. Overlapping map between periods.

3.2. Evolution Map

The evolution map evidences that the study of mid-rise and tall timber buildings progresses from general to more specific themes (see Figure 7). The initial main cluster keywords of period 1 were *timber-buildings* and *life-cycle*, which are more general than subsequent terms. As aforementioned, the words *building* and *timber-buildings* were merged into one group. *Timber-buildings* are connected to *timber-frame-building* in the second period through a solid line, sharing the core theme and indicating the initial relevance of frame structures in the early years of investigation. In the case of *timber-buildings*, the word was the core theme in periods one and two. The topics did not connect with the posterior clusters, suggesting more specific research.

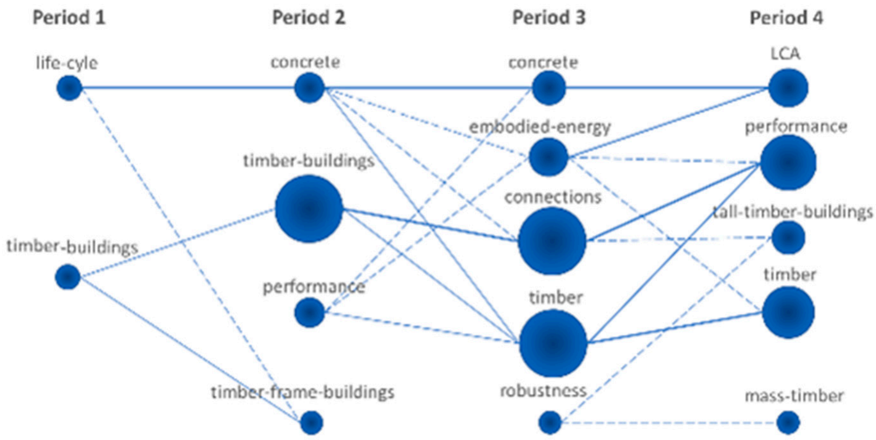

Figure 7. Evolution Map from period 1 to period 4.

In the second period, new clusters such as *concrete*, *performance*, *timber-frame-building*, and *timber-buildings* emerge. *Timber-buildings* are linked to *connections* through *cross-laminated-timber*, which indicates the research community's potential interest and necessity to study the structural elements and how the connections are made between them. *Timber-frame-building* did not connect in the next period, indicating a possible reduction in the investigation of timber-framed structures because those products do not allow for tall buildings. *Concrete* presents two solid-edge connections to the next period, *concrete* and *timber*. The connection with *timber* was through the main keyword *timber*. The clusters from the third period present more edge convergence than the second period, indicating that the next period cluster presents similar and not isolated themes. Also, *concrete* presented a dotted connection with *embodied-energy* and *connections*, through *life-cycle-analysis* and *design*, respectively. In the case of *performance*, the network presented three links, one solid and two segmented. The solid line is linked to *timber* under *performance*. Also, a connection was made by sharing a cluster of *impact* with the main cluster *concrete* and sharing the *residential-buildings* with the cluster *embodied-energy* in the third period.

The third period presented a new network which included the word *robustness*, and it was not connected with the previous period. *Robustness* appears as a structural network, with themes such as *structural-integrity*, *disproportionate-collapse*, *progressive-collapse*, and *failure*. A connection to the last period from *robustness* was via segmented lines to *tall-timber-buildings* and *mass-timber* through the cluster of *disproportionated-collapse* and *progressive-collapse*, respectively. *Concrete* and *embodied-energy* were both connected to the fourth period in a solid line to the cluster *LCA*. They indicate the constant research until the end of the analysis periods of environmental topics from timber in mid-rise and tall buildings. *Connections* were linked to *performance* in the last period, sharing the cluster *connection* and *tall-timber-buildings'* through *cross-laminated-timber*, the cluster with the most documents in both networks.

In summary, the evolution map (Figure 7) illustrates the progressive refinement of research themes in mid-rise and tall-timber buildings across four distinct periods, highlighting the shift from general foundational topics to more specialized and interconnected themes. During Period 1 (1988–2010), the research focused on general sustainability aspects like LCA and timber-frame buildings, which established a baseline for timber's environmental advantages. In Period 2 (2011–2016), the introduction of mass timber and studies on structural performance marked a significant transition towards understanding its feasibility for taller buildings. Period 3 (2017–2020) witnessed an emphasis on robustness, disproportionate collapse, and perceptions of timber buildings, reflecting efforts to address structural and societal challenges associated with tall structures. Finally, Period 4 (2021–2022) presented advanced investigations into hybrid construction methods, refined LCA methodologies, and high-performance evaluations for tall timber buildings, signalling maturity in both technical and environmental research. The connections between clusters, such as those linking concrete and timber with embodied energy or tall timber buildings with cross-laminated timber, underscore a growing interdisciplinary approach that integrates structural, environmental, and societal dimensions. This trajectory not only demonstrates the field's evolution but also aligns with global priorities for sustainable urban development.

3.3. Period Analysis

The evolution of the research in mid-rise and tall timber buildings is conducted by considering three aspects for each period: (1) a description of the three most cited articles, (2) an explanation of the strategic diagram with an explanation of the most iconic constructed timber buildings of the period, and (3) a description of the motor themes with their respective cluster network. Furthermore, only for the last period, (4) all the cluster networks are explained to analyze the current research topics and trends.

3.3.1. Period 1 (1988–2010)

Most Cited Articles

The first period (1998–2010) is the most extensive in number of years. The most cited research of the period was the investigation of Börjesson and Gustavsson [32] related to timber vs. concrete greenhouse gas balance. Different analyzed scenarios included the end of the life of the timber frame, the effect on forest emissions, and the carbonization of the concrete. The authors concluded that the efficiency of timber products in terms of greenhouse gas (GHG) depends not only on the production process but also on the timber waste handle after demolition. Also, the article concludes that concrete frame-building GHG would be higher than timber frame building, but the difference will be shorter if the carbonization process is considered from a long-term perspective. The second most cited article in the first period was written by Werner and Richter [33]. They presented a compilation and literature review of life-cycle analysis studies of timber-based building products compared to similar or equivalent products. The article sustains that there are increments in material emissions due to using impregnated products, particle boards, or fiberboards compared with standard solid timber products. Additionally, the authors mentioned the importance of maintaining representative and reliable life-cycle inventories (LCI) and implementing a new LCA data process to their database. The third most cited article of the period was the investigation of Puettmann et al. [34], which performed a LCI from cradle to the gate of different timber and engineering wood products (EWP), such as softwood lumber, soft plywood, laminated veneer lumber, and oriented strand board (OSB) based on CORRIM 2004 reports from the United States. In an LCI analysis, a separation of processes is made to identify and quantify the inputs and outputs involved in the product or method. The authors' results show that biomass (timber waste) was the primary fuel source to lower environmental emissions, releasing CO_2 from biomass instead of CO_2 from fossil fuels. Another conclusion was that based on European databases with different electricity production sources, resin production, and feedstock presented a high energy consumption [34].

Strategic Diagram

Regarding the construction of mid-rise and tall timber buildings in practice, it is interesting to note that by the end of this first period, the nine-storey 29 m-high Stadthaus building in London was constructed in 2009, by Waugh Thistleton Architects. This iconic building was a very important milestone for the discipline because it was the first timber building in the range of 30 m constructed with CLT, which greatly contributed to the widespread use of this mass timber product, demonstrating that it could be used to construct tall buildings. The development of standards and research at that time was poor, but the interest in life cycle and the first iconic CLT tall building served as a starting point for this building discipline.

As expected, for this incipient period between 1988 and 2010, the discipline was actually building itself and thus there was no clear main cluster location. The few articles in this period generate only two clusters. As shown in Figure 8, the first one was the *timber-buildings* cluster, which constituted the central topic of the discipline but was not developed enough nor had a significant number of related articles. The cluster network was located between the motor themes, which are the relevant and developed topics for the field and are located in the first quadrant of the strategic diagram, and the fourth quadrant, which are the basic and transversal topics. The second cluster network in the period was *life-cycle*. The cluster was located between the first quadrant and the second quadrant, which is the highly developed quadrant. Due to the science mapping analysis configurations and first-period characteristics, no main clusters were detected in the third quadrant, which is the emerging or disappearing topics.

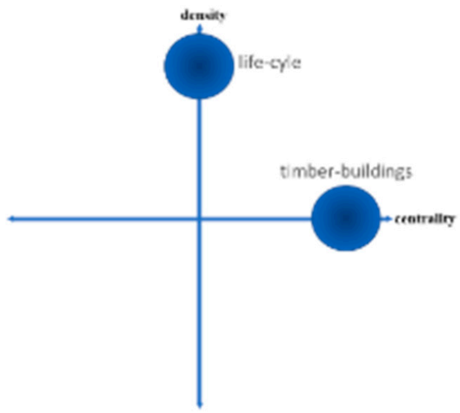

Figure 8. Strategic diagram for the first period (1988–2010).

Motor Themes

At this first incipient period, there were no clear motor themes, but topics such as *life-cycle, LCA, timber*, and *construction* may be regarded as the precursor of the first motor theme even when its transversality was not yet widespread enough in the discipline. As shown in Figure 9, the *life-cycle* constitutes a very connected cluster, which is related to environmental topics such as *LCA*, *energy*, and *emissions*.

Timber was the term with the most documents in this network. The appearance of *concrete* in the first period and in this topic investigation was due to the analysis of timber structures as an alternative to reduce environmental emissions. Despite the visual lack of connection in the network from *concrete* and *substitution* topics, the articles in the period of both topics focus either on timber utilization as an alternative for traditional constructions or compare its environmental properties [19,33,35]. In the case of *energy*, the topics were focused on calculating the environmental emissions and life-cycle primary energy of timber [19,32,34,36].

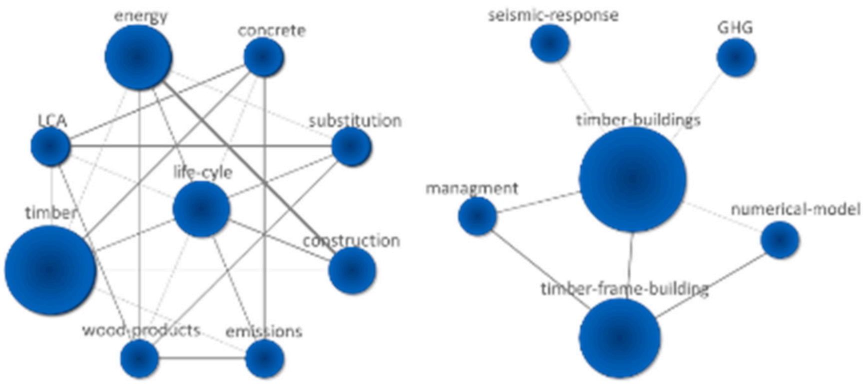

Figure 9. Cluster networks of the first period: life-cycle (**left**) and timber buildings (**right**).

As seen in Figure 9, the *timber-building* network was less connected and mostly included terms related to research on the structural safety of this type of building. Nevertheless, the term *GHG* was still a relevant topic as a significant amount of research focused on investigating different emission levels, from the impacts of timber building products [30] to analyses of the impacts of timber building, accounting for forest land perspectives [32] and carbon pools analysis [35,36].

Regarding the importance of structural aspects in this period, two aspects are important. The first one is that the most studied structural typology in this period covered timber-frame building articles [19,37–41]. This was expected since, only by the end of this period did mass timber products, and more particularly, CLT, start becoming popular. Mosalam and Mahin [40] performed large-scale seismic testing on a three-storey asymmetric timber frame building. The article concludes that hold-downs were essential to prevent the overturning collapse, finish material has to be considered in a seismic assessment of the existing building with a retrofitting focus, and an improvement in seismic performance of timber frame buildings can be achieved by adding a retrofit steel frame in open front [40].

3.3.2. Period 2 (2011–2016)

Most Cited Articles

A significant increment of publications in the field is evidenced during the second period, since the number of publications doubled, even when it only lasted about a quarter of the first period. The most cited article of this period was the work of Ceccotti et al. [42], which conducted an ambitious project to test the seismic performance of a full-scale seven-storey CLT building on a shake table. The article concludes that this newly proposed structural typology, strongly influenced by the Stadthaus during the first period, was structurally safe to construct even in high seismic regions. Yet, the authors registered very high accelerations at the top of the structure, which evidenced that even when these buildings can withstand strong earthquakes, more research is needed to enhance their seismic performance. The second most cited article also investigated CLT's structural behaviour in a multi-storey timber building. Fragiacomo et al. [43] evaluated different mass timber connections between CLT panels and performed an elastic seismic non-linear static analysis of a four-storey CLT building model. Based on the results of the investigation, the authors started proposing seismic performance factors for this new type of structure that allowed them to conduct practical seismic designs of buildings, such as overstrength. Also, the article focused on analyzing the local and overall ductility to demonstrate the performance of these type of buildings during extreme loading events. The third most cited article was the research of Dodoo et al. [20], which analyzed the carbon life-cycle implications of three types of timber building systems on a four-storey building with two approaches: conventional and low-energy. The building system types were CLT, beam and column using laminated veneer lumber (LVL), and prefabricated modules using light-frame elements. The low-energy design aimed to meet the Swedish passive house criteria. The results show that in terms of energy efficiency, LVL with the conventional systems results in higher carbon emissions, and low-energy CLT alternatives achieve the lowest life-cycle carbon emissions [20].

Strategic Diagram

During this period, more than 50 tall buildings were constructed worldwide, with two of them becoming iconic milestones for the discipline [44]. The first one was the 10-storey 30 m-high Forté building, finished in 2012 in Melbourne, Australia. Despite not being much taller than previous projects, this building rapidly became a worldwide icon because of its rapid and highly prefab CLT construction system. The second was the 15-storey 52 m-high Treet building, finished in 2015 in Bergen, Norway. Apart from the great increase in height in comparison with previous buildings, the Treet used a post and beam system based on LVL and glulam, which demonstrated that other structural timber typologies are also feasible for tall buildings. In addition, the Treet was also a great milestone in terms of policymaking because Scandinavian authorities relaxed the height limits for timber structures, allowing the construction of tall projects. This great achievement was, again, coincidental with the end of a relevant period in research since the end of the second period is concurrent with the Treet finishing.

Concrete and *timber-buildings* were the motor themes of the period. *Timber-frame-buildings was* located in the emerging or declining themes as seen in the strategic diagram in Figure 10. The location of *the timber-frame-buildings* network in the third quadrant could be associated with the structural typology limitation to construct buildings taller than six–seven storeys [45]. This evidence in the field of timber construction led researchers to switch their main focus to tall buildings rather than low-rise construction. Performance was located in the centre of the strategic diagram.

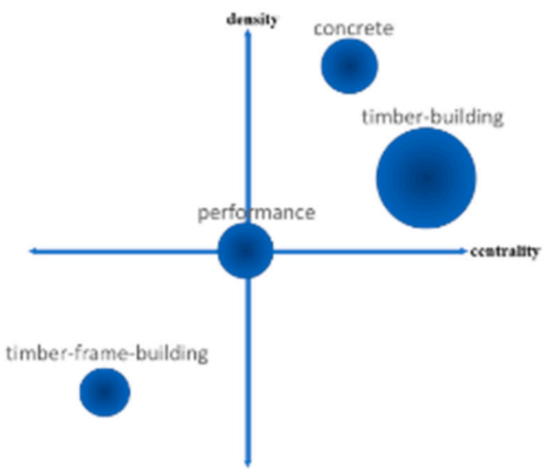

Figure 10. Strategic diagram for the second period (2011–2016).

Motor Themes

Although timber is the main topic of this investigation, *concrete* appears as a principal cluster in Figure 11. As seen in Figure 11, a major interest in *concrete* relates to comparing environmental impacts with timber [20,46,47], as evidenced by the strong links with terms such as *balance*, *LCA*, or CO_2 *emissions*, which at the same time are strongly interrelated with each other. The keyword *balance* was connected to almost all clusters, and research associated with the second period focused on the LCA, carbon emissions, and primary energy building [20,47–50]. *Concrete* also starts playing a significant role as a material necessary for casting hybrid timber–concrete buildings. At this time, researchers realized that the combination of timber with concrete could be very beneficial for enabling tall timber construction, mainly because timber could benefit from the large strength, stiffness, cost-effectivity, and fire resistance of concrete [51]. *Mass-timber* emerged in the *concrete* network during this period with strong connections to *structural-systems* and *balances*. Regarding the relationship with *balances*, the articles in the period were related to environmental emissions quantification in articles [20,47]. Both articles allude to mass-timber CLT in their content. The *structural-system* cluster comprised three articles [20,47,52] and all of the primary structural elements to be analyzed were CLT or mass-timber, confirming the clusters' strong connections.

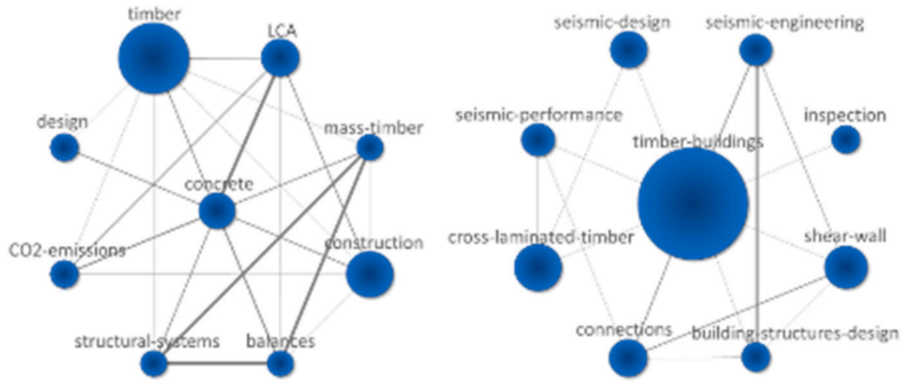

Figure 11. Cluster networks of the second period: concrete (**left**) and timber buildings (**right**).

Regarding the *timber-buildings* motor theme, as expected by the most cited publications, a great body of research focused on structural topics, especially on the seismic performance of timber buildings, with the expectation that this can be one important advantage for these buildings.

3.3.3. Period 3 (2017–2020)

Most Cited Articles

The most cited article of the period was the investigation of Churkina et al. [53], which explained the different emission rates of traditional building materials and illustrated the difference between light timber and massive timber elements in terms of emissions. The article analyses four future transition scenarios from concrete and steel urban building construction to mass timber urban buildings from 2020 to 2050. The cases were first business as usual, which considers 99.5% of buildings constructed by concrete and steel, and other cases with an increment from 10%, 50%, and 90% in timber urban buildings. All the scenarios considered the manufacturing capacity of countries and their potential industry development for mass timber factories. The article demonstrated the capacity of mass timber urban cities to achieve carbon pools but also remarked on the need to ensure sustainable forest management due to increased timber demand. The second most cited work of the period was by Asdrubali et al. [54], which reviewed and analyzed different timber structural topologies for residential buildings, structural properties, thermo-physical properties, acoustic properties, and environmental aspects. General information on the timber properties is explained in the different sub-topics. For example, from a seismic point of view, the authors mentioned the non-ductile behaviour of the timber stress–strain, which is a disadvantage for a seismic aspect. This particularity brings the necessity of concentrating the ductility of structures on the steel joints Asdrubali et al. [54]. The article also describes tall timber building projects, such as the Treet, Forté, and Brock Commons, and mentions that improving scientific research would generate a new era for timber buildings. The research concluded that with the technological development of timber construction, a possible increment of timber buildings would occur under low energy and passive goals. Finally, the third most cited article of the period was the research of Bartlett et al. [55]. The article reviews the different processes and subprocesses of the burning behaviour in timber and explains the analytical expression in the literature that represents these phenomena. The review also explains how different properties, such as species, moisture, system orientation, encapsulation, delamination, and others, can affect the charring rate described in the literature. For example, the authors mentioned a few investigations under the delamination process of laminated timber, such as CLT, in which they concluded that with a higher lamellae thickness, a lower overall charring rate could be seen due to a lower occurrence of delamination phenomena. The article concluded that incident heat flux, which in the investigation case represents and quantifies the fire scenario, significantly affects the charring rate [55]. These three articles suggest a shift in research interest in the field from the predominantly seismic-structural most cited articles of the previous period to an emphasis on the environmental benefits and scenarios of building the cities with timber, rather than concrete or steel. The period also suggests more emphasis on performance topics different to structural, such as fire performance.

Strategic Diagram

This third period included the construction of three very iconic timber buildings. The first was the 18-storey 53 m-high UBC Brock Commons building, finished in 2017 in British Columbia, Canada. This building was one of the most iconic timber projects ever constructed not only because of its height, but also because it used a very effective structural and construction system. The building, which consists of a student residence of the UBC, was realized by first setting two concrete cores and a podium, to subsequently erecting a very rapid construction system based on glulam columns and CLT slabs. The second was the iconic 18-storey 86 m-high Mjøstårnet building, finished in 2019 in Brumunddal, Norway. This building, which can be seen as an evolution of the Treet building as it was constructed with a similar structural system, meant not only a great increase in height, but also demonstrated that such height was possible by only using timber. The third was the 24-storey 84 m-high HoHo building in Wien, Austria. In contrast to Mjøstårnet, this was a very hybridized building comprising multiple timber–concrete composite components. These three buildings served to prove that most buildings in cities can be feasibly constructed totally or partially with timber, which may help to expand the scope of sustainability investigations covering the assessment of the environmental impact of constructing with timber at community and city levels, not only on specific components or buildings. The strategic diagram of the third period is shown in Figure 12.

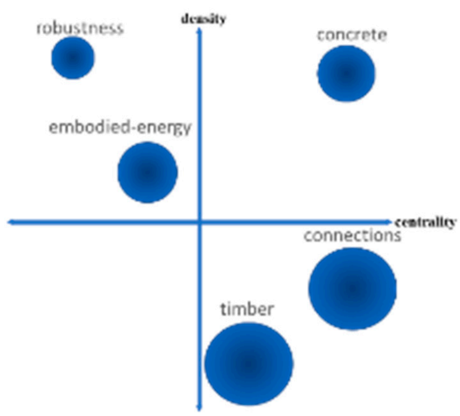

Figure 12. Strategic diagram for the third period (2017–2020).

A new topic in the highly developed quadrant was the main cluster of *robustness*, which focused on the structural subjects related to mid- and high-rise timber building [56–63]. The clusters in the network were *structural integrity*, *proportioned-collapse*, *failure*, and *progressive collapse*. Also, the cluster *embodied-energy*, can be found in the highly developed quadrant with a lower density and centrality [64–70]. This particular cluster network contains mostly environmental topics in the period related to *LCA*, *sustainable-assessment*, *operational-energy*, *GHG, waste, residential-buildings, passive-house and life-cycle.*

Timber was classified as a transversal-basic, containing two topics with an increase in frequency: *innovations* and *perceptions*. *Perceptions* are a more recurrent topic in this period, addressing research themes such as how the Swedish actors in the multi-storey residential building world see timber products [71] and other topics such as barriers identified at the time like cost, building codes, lack of expertise, durability, technical aspects, culture in the industry and material availability [72] of the timber industry and products. The topic *Innovation* was analyzed for new products such as EWP and their perception of Swedish architects [73] or elements such as CLT, but in the context of North America focused on the behaviour under water and moisture control of different envelopes innovations [74]. The cluster network of *connections* falls in the transversal-basic with *cross-laminated-timber* as the cluster with the most articles in the network.

Motor Themes

Concrete was the only motor network in the third period. As illustrated in Figure 12, the explanation, almost without exceptions, is that the research interest strongly focused on the potential environmental benefits of constructing with timber since all the terms in the cluster network directly or indirectly relate to this topic. Moreover, the topics show multiple connections with each other. Especially, for this period, environmental research starts to cover and gain significance at macro levels, studying the environmental impact on economies, communities, and cities [71,75,76]. The term *concrete* in the network was related mainly to environmental topics such as carbon footprint, life-cycle cost, energy analysis, Co2-emission, and emissions, as seen in Figure 13.

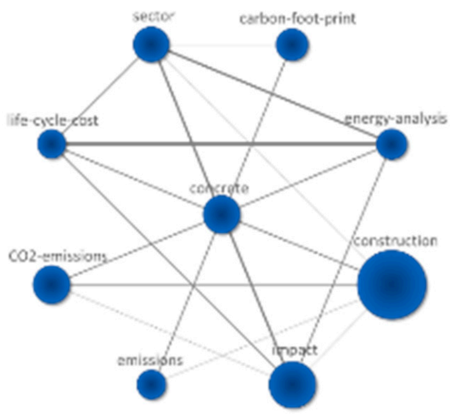

Figure 13. Cluster network of concrete for the third period.

The topics *impact* and *sector* were mainly associated with environmental topics [53,67,69,75,77–79]. In all period articles, the keyword was added via Keyword Plus, which does not add specific information. Other topics related to *impact* including *environmental-impact*, *sound-impact*, and *climate-impact*, due to the low frequency of the keywords, were not added to the cluster analysis.

3.3.4. Current Trends (2021–2022)

Most Cited Articles

Analyzing the current trends of the last period (2021–2022), the most cited article was the research of Gustavsson et al. [80]. The article analyzed the climate implications of different forest management, bioenergy, and timber construction emissions under various scenarios regarding forestry, type of building construction, and energy resource alternatives. The article shows the net CO_2 emissions in different periods on a 201-year timespan. The authors mentioned that the key factors guiding the results were forest management intensity, harvested biomass, time horizon, and non-timber product replacement. Gustavsson et al. [80] conclude that in the long run, instead of setting aside forest land to reduce the amount of biomass harvest and stored carbon, an active forestry with high harvest levels and efficient use of harvest biomass to replace non-timber products and fuels can provides significant climate mitigation. The second most cited article from the period was the seismic-structural investigation of Aloisio et al. [81], in which a CLT element was analyzed, and fragility functions with behaviour factors were addressed. Based on an extended energy-dependent generalized Bouc-Wen (EEGBW) model, the authors generate an analytical and numerical model of multi-storey CLT building as a shear plane structure. The main results estimated the different storey buildings' behaviour factors and fragility curves. The authors concluded that based on the fragility curves, the vulnerability to earthquakes heavily depended on the seismic scenario and storey number rather than the CLT wall panel typology [81]. The third most cited article of the fourth period was the study of Xia et al. [82]. The article analyzed the application of epoxy resin (EP) and phase-change material (PCM) compound into delignified timber to create transparent timber that additionally stores heat during the day to release it during night. The authors conclude that with the increment of PCM, the transmittance energy storage wood (TESW), with an 80% weight ratio of EP and PCM, reaches 134.1 and 122.9 j/g on the melting and crystallizing temperature. In addition, the TESW archives a light transmittance of up to 80.89%. These three articles are diverse but demonstrate an evolution from fundamental to more advanced topics. From the environmental perspective, analyses also start more explicitly covering the implications of forest management and biomass utilization on the sustainability of using timber for construction. On the structural seismic field, fragility functions of the new structural systems and new hysteresis models allow for more precise and in-depth analysis of timber buildings under different load scenarios. Finally, investigations like the one from Xia et al. [82] demonstrate the possibility of improving timber performance and extending construction applications by modification of its material properties.

Strategic Diagram

In terms of iconic buildings, this period included the completion of two iconic buildings. The first was the 21-storey 73 m-high Haut building completed in 2022 in Amsterdam, the Netherlands. Like some previous buildings, this project also used a highly hybridized timber–concrete structural system, but the particularity was that it was the Netherlands' first building to achieve the BREEAM Outstanding classification. The second was the hybrid timber–concrete 25-storey 87 m-high Ascent building, completed in 2022 in Milwaukee, WI, USA, which is currently considered the tallest timber building in the world. Although these two iconic buildings undoubtedly represent outstanding technological and engineering achievements, neither the increase in height nor the shift in construction technologies suffered notable changes concerning the previous period. Therefore, it could be argued that from the point of view of the construction of iconic projects, the construction technologies of tall timber buildings are achieving a certain degree of maturity. The strategic diagram from the last period is shown in Figure 14.

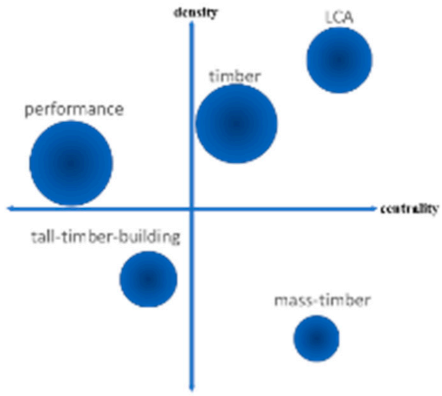

Figure 14. Strategic diagram 2021–2022.

Motor Themes

LCA was the main cluster in this network, connected to environmental topics, except for *Concrete* and *Construction*, as seen in Figure 15. The presence of *Concrete* can be explained due to timber comparison and *Construction* to the transversal origin of the topic.

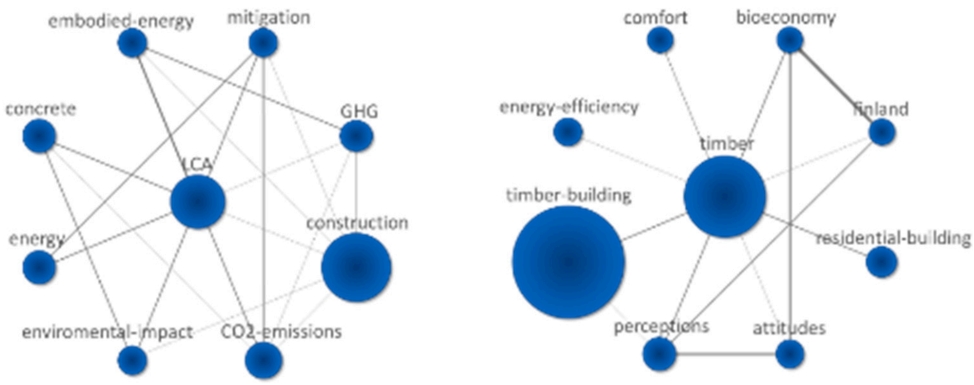

Figure 15. Motor themes from fourth period (2021–2022).

It is interesting that a change was also observed in the articles related to the term *GHG* in which, currently, the researchers are emphasizing the modelling of the final stages of building, such as demolition or recycling [4,83–85]. The estimation of the emissions through the LCA methodology has been presented throughout the periods and appears as a motor theme due to the necessity to quantify the benefits and improve the mitigation of emissions through timber as a building material of mid- and high-rise buildings. For example, in the last period, Younis and Dodoo [86] investigated the background of LCA in CLT buildings, exploring past CLT projects and analyzing how to improve the LCA method to obtain more accurate results and optimize the carbon footprint in these mass timber buildings.

The second cluster network in the motor theme was *timber*, one of the main topics in the research formula gathering common topics such as *timber-buildings* and *residential-building*, illustrated in Figure 14. Surprisingly, *Finland* appears as a relevant term for current research, which is strongly linked with *bioeconomy* and *perceptions*. This reflects the relevance of this country for its development in fostering timber construction from a bioeconomic and societal point of view, which serves as a worldwide reference.

The topics in this duo, *perceptions* and *attitudes*, were associated with professionals [87,88], government [89], and society's perspectives [90–93] on timber buildings. The keyword *bioeconomy* was linked to this duo through a few articles in which the main relation was the perception of the residents [93] and professionals [87] on timber housing to archive a forest-based bioeconomy. Another study in the period related to *bioeconomy* and the duo of *perceptions* and *attitudes* is the investigation of Toivonen et al. [89], which analyzed the policy narrative on timber multi-storey construction (TMC) and contrasted to the governance of the technological innovation systems around TMC. The investigation identifies that one of the policy narratives related to TMC was the bioeconomy narrative, which focused on TMC as a method to achieve a more sustainable bioeconomy [89].

It should be noted that even though the environmental assessment of timber construction is currently a strongly developed and transversal topic whose investigations are strongly interrelated, which is reflected by the leading position of the term *LCA* in the strategic diagram at the first quadrant, Figure 14, and the multiple links of its cluster network, Figure 15, the societal economic aspects are still not so developed. This could indicate that both investigations, including the multidisciplinary assessment of environmental and economic/societal aspects, and investigations linking different societal/economic aspects such as comfort with perceptions, energy-efficiency, and attitudes, may be of great impact for the discipline.

Current Trends in Other Relevant Cluster Networks

The term *mass-timber* emerges for the first time as the main topic in cluster networks. This term covers a great variety of topics that are poorly interconnected, from very specific structural topics such as *progressive-collapse*, to very general topics such as *systems*, *steel sustainability*, and *embodied carbon* see Figure 16.

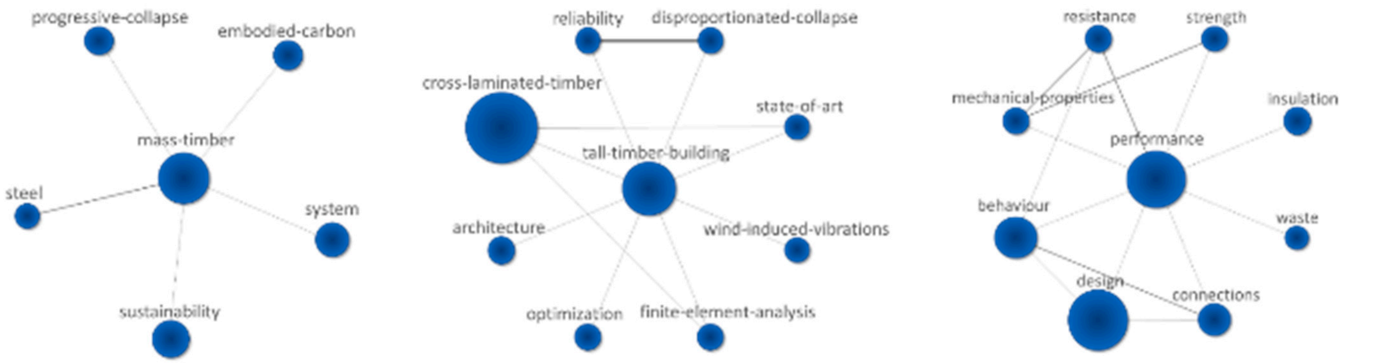

Figure 16. Current trends in research of other topics different from motor themes including *mass timber* (**left**), *tall timber buildings* (**centre**), and *performance* (**right**).

The new emerging connection between *mass-timber* and *steel* is also interesting, represented by the investigation by Allan and Phillips [94]. The authors perform an LCA of different buildings to understand the difference in using mass timber instead of North American conventional frame steel structures. The article concludes that the utilization of mass timber reduces emissions in several categories, especially in the global warming potential. Finally, the authors mentioned the potential to include mass timber as a floor solution in steel buildings, thus, also starting investigations on hybrid steel timber construction [94].

The topic *embodied carbon* is the main component in the LCA, which can be defined as the GHG emissions of a building over its life during the stage of extraction, transportation, manufacture of construction materials, building construction, and inclusive operations, demolitions, disposal, or recycling [4]. Another interesting new connection relates the term *mass-timber* with *embodied carbon*. The fact that more timber is being used for the new proposed structural mass-timber typologies also implies a more profound impact of timber construction in embodied carbon, which is currently an important research trend for timber structures. For instance, the article by Chaggaris et al. [95] investigated the cost, emissions, and carbon sequestration potential for different beam-column configurations. The article concluded that the cost of gypsum board for fire protection and the CLT for floor material tends to dominate the beam-column independent of the building configurations. Also, the article mentioned that carbon sequestration and cost objectives can be in disagreement because both increase with the increase in timber volume [95].

An alternative interesting topic in mass timber research is represented by the concept of biogenic carbon. The results in this bibliometric analysis show the use of the terminology *biogenic carbon* in the second period [96], but the notion of carbon balances, carbon capture, or carbon pools has been presented since the first period [32]. In the last period, a few articles mentioned biogenic carbon in their respective keywords [83,95,97,98].

A second relevant cluster that appears for the first time as a main topic in the network and that also could be seen as an evolution of the term *timber-buildings*, is the cluster *tall-timber-buildings*. The cluster is classified into declining and emerging topics, which makes sense because in this period more specific topics related to tall buildings are emerging.

In general, structural investigations in tall timber buildings are shifting from a more seismic-focused origin, into specific topics such as *wind-induced-vibrations* and *disproportionate collapse loads*. The partial shift from seismic to wind interest was to be expected as wind loading tends to be more critical for tall buildings rather than seismic, which tends to govern the design of lower-rise buildings. The investigation of the wind effect of induced wind load has been presented in the second and third periods in additional keywords such as *wind-loads* and *wind-pressure-coefficient* [39,99–103]. Multiple articles related to wind topics have been detected in the period analysis [22,104–106]; for example, Binck et al. [104], investigated and developed an adaptable and flexible lateral stiffening system for tall timber buildings between 50 and 147 m. The system was subjected to multiple finite element simulations in different configurations to analyze the lateral stiffens subjected to wind loading. The article concludes that the proposed system was feasible for 147 m and the lateral stiffening system was sensitive to geometrical parameters such as bay number and length. On the other hand, the rising interest in *disproportionate collapse* and its strong link with *reliability* could also be expected [107–109]. One of the most utilized structural typologies that are prevailing for tall timber buildings is based on using isolated timber columns for resisting gravitational loads. Timber being a brittle material, reliability studies, therefore, become relevant for preventing the disproportionate collapse of tall timber buildings. For instance, the investigation of Voulpiotis et al. [107] analyses a timber post and beam tall building to quantify the robustness based on a published method. The authors concluded that in terms of preventing disproportioned collapse, design improvements at a global building scale, such as trussed strong floors, could be more effective than increasing the strength and ductility of the selected connections. The most cited topic in the *tall timber buildings* network was, however, *cross-laminated-timber*, with 34 documents in the period, further reinforcing the link of tall buildings with this specific timber product. *Finite element analysis* is also a new main term that relates mostly to the period with *cross-laminated-timber*, indicating the emphasis of research on proposing new structural calculation models for tall timber buildings constructed with CLT [22,110–113].

Not all articles related to *finite element analysis* in the period were focused only on CLT. For example, Labrecque et al. [114] modelled a structural solution of light frame timber modules in two hyper structures: concrete and glulam. The article concludes that both solutions were viable under different structural restrictions depending on the hyper structure; still, more investigation is needed for subjects like connections between the hyper structure and the modular structure [114].

The last cluster network of the current strategic diagram is *performance*, which currently shows the largest number of contributions. This term covers very diverse topics including structural [22,108,115–119], envelope design [120], acoustic performance [121], environmental and energy [112,116,122,123], and social aspect [92].

4. Discussion

4.1. General Discussion

The results of the bibliometric analysis show multiple insights into how mid- and high-rise timber building topics have evolved during the study periods.

During the first periods, most topics were based on light-frame timber building studies and developing new EWP such as glulam or laminated veneer lumber. At the end of the first period, *CLT* and *mass-timber* were more recurrent and positioned as main topics in the subsequent periods, showing their potential increase as investigation topics in the mid-rise and tall building area. An increment in specific topics such as *connections* and *robustness* were identified in the final periods, indicating the investigation focuses on the structural feasibility of tall timber buildings.

The environmental topics have been present in all periods, constantly quantifying the emissions of timber products from EWP to a building scale. The keywords representing the sustainable topic were *LCA*, *emissions*, and *GHG*. The environmental impact quantification of timber as a solution for mid-rise and tall buildings requires constant development and study due to the constant change in LCA stages, assumptions [124], and efficiency of inputs and outputs. The last period shows an increase in studies related to end-of-stage analysis and carbon storage, showing a potential research interest in harvest timber products as a temporal/long storage pool.

Building on this sustained focus on environmental concerns, one of the most significant transformations in mid- and high-rise timber building research has been the shift from a predominant focus on structural safety towards greater emphasis on sustainability and energy efficiency. This change has been driven by the development of new materials such as CLT and mass timber products, increasingly stringent environmental regulations, and the growing interest in reducing the carbon footprint of the construction sector. Timber has emerged as a viable alternative to concrete and steel due to its carbon storage capacity, leading to an increased research focus on its environmental impact.

The seismic topic was a recurrent research line that has always been present from light frame to mass timber. The systematic characterization of the seismic and mechanical behaviour of structural elements was intended to ensure the structural feasibility of mid- and high-rise timber buildings. Recurrent topics in this area were *seismic-performance, seismic-design, seismic-engineering*, among others. Regarding tall timber buildings, particular topics show up in the last periods: *collapse, robustness*, and *wind induced vibrations*, which increased in frequency since the third period, noting the importance of settling a solid base on tall building topics to achieve higher heights with timber as a structural material.

The concept of hybrid building appears slightly in the periods of analysis. It was noticed that there was different terminology to address the hybrid structure or components; for example, *hybrid-structures*, *hybrid-buildings*, *timber-concrete*, and *hybrid-CLT-building*. A common terminology of *hybrid-structures* or *hybrid-buildings* is needed to join the research of materials combinations on mid- and high-rise timber buildings. In recent periods, a collaborative investigation with the topic of *Concrete* has been performed, leading to potential hybrid building from the element scale such as composite to the interaction of concrete core with mass timber walls and floors to achieve higher and cost-efficient buildings.

The *perception* and *attitude* towards mid- and high-rise timber buildings from the different actors could define how these structures have been integrated into standard alternatives of society's needs. The analysis results show an increment from the third period to the actual one on articles related to the *perception* and *attitude* of timber buildings as a main topic, showing the necessity of studies on how timber structures are perceived in the world and market. The insights of *perception* and *attitude* research on timber as a building material help architects, engineers, and constructors to prioritize which aspects should improve to increase the interest of stakeholders and citizens.

Fire investigations obtained from the research formula do not appear as relevant and common keywords or main clusters. Fire investigations were dated from this analysis since 1995 under the investigation of light-frame buildings. Topics of fire-related timber buildings were historical timber buildings' [125,126] fire performance of materials [127–133]. The study of fire behaviour in tall timber buildings is crucial to improving and promoting the safe construction of high-rise timber structures aligned with other aspects such as structural safety and mechanical electrical plumbing codes.

One of the most significant transformations in mid- and high-rise timber building research has been the shift from a predominant focus on structural safety towards greater emphasis on sustainability and energy efficiency. This change has been driven by the development of new materials such as CLT (Figure 17) and mass timber products, increasingly stringent environmental regulations, and the growing interest in reducing the carbon footprint of the construction sector. Timber has emerged as a viable alternative to concrete and steel due to its carbon storage capacity, leading to an increased research focus on its environmental impact.

Figure 17. CLT construction. Health centre in Abegondo, La Coruña, Spain. January 2025.

4.2. Limitations and Future Work

This study has several limitations related to the time span, database selection, search formula, and bibliometric analysis settings. First, the selection of WOS as the sole database for this bibliometric analysis was based on its well-structured metadata, standardized citation tracking, and compatibility with science mapping tools such as SciMAT. WOS provides high-impact, peer-reviewed publications that ensure data consistency and reduce redundancy. However, this choice also presents certain limitations. Other databases, such as Scopus and Google Scholar, contain additional sources that could contribute to a broader data set. Scopus includes a wider range of journals, particularly in engineering and sustainability fields, while Google Scholar provides access to grey literature, conference proceedings, and institutional reports that might not be indexed in WOS. Additionally, the keyword selection methodology may have influenced the results by prioritizing certain terms over others. Finally, the evolution of terminology in mid- and high-rise timber building research may have affected topic clustering, as certain terms have changed over time. To address these limitations, future research could expand the search to additional databases and employ machine learning techniques to enhance topic classification and detect emerging research themes.

A key next step in this research is to analyze publications from the most recent period (2023–2024) in a yearly step approach. Examining this close period will help identify the latest trends and challenges in mid- and high-rise timber building research, particularly regarding sustainability, structural performance, and regulatory developments. Moreover, there is a growing need for research on the perception and attitude towards mid- and high-rise timber buildings in Chile, particularly among public, private, and key stakeholders involved in timber construction projects. This research could provide valuable insights into the factors influencing the adoption and funding of timber-based urban developments.

Recent studies have advanced the field by addressing sustainability, automation, structural adaptability, and damage detection in timber structures. Bucklin et al. [134], in 2023, explored the thermal transmittance and air permeability of solid timber envelopes, showing how design modifications like deep air chambers enhance energy efficiency while maintaining airtightness. Lauer et al. [135], in 2023, examined automated on-site assembly of timber structures using biomimetic shells, demonstrating increased precision, efficiency, and sustainability in construction. Öberg et al. [136], in 2024, introduced the design for the structural adaptation (DfSA) concept, which promotes flexibility in timber buildings to extend service life, improve carbon storage, and enhance resource efficiency while identifying key regulatory and economic barriers. Liu et al. [137], in 2024, developed a precision detection method using portable light detection and ranging (LiDAR) technology for assessing damage in historic timber buildings, contributing to better non-destructive maintenance and restoration strategies.

These recent contributions highlight the necessity of continuous updates in bibliometric studies to capture emerging themes and shifts in research focus. Expanding the data set with new publications will refine the understanding of timber's role in future urban construction, bridging the gap between theoretical advancements and real-world implementation.

5. Conclusions

1. Population growth and urban needs: The increase in population has motivated the construction and design of taller buildings that can respond to society's necessities. Timber buildings emerge as a sustainable solution that can address habitability and workspace demands while reducing carbon emissions. Technological advancements have driven the evolution of timber construction from light-frame elements to various engineered wood products (EWPs) such as glulam and CLT.
2. Research contributions and evolution: This study conducted a bibliometric analysis using a science mapping technique to categorize and analyze the evolution of research topics on mid- and high-rise timber buildings, identifying key trends and challenges. A total of 1233 articles were initially selected, and after filtering, 701 articles were analyzed across four distinct periods.
3. Challenges in timber high-rise construction: Despite the advancements in research and the increasing adoption of timber in high-rise construction, its implementation in urban contexts presents significant challenges. These include regulatory barriers that still limit the permissible height of timber structures in many jurisdictions, initial costs associated with the manufacturing and assembly of engineered wood products, and industry and public perceptions regarding the durability and fire resistance of timber. Overcoming these challenges requires a combination of technological advancements, adapted regulations, and effective communication strategies that highlight the environmental and structural benefits of timber.
4. Future research directions: Addressing these challenges will be crucial for aligning the environmental potential of mid- and high-rise timber buildings with structural feasibility and societal acceptance. Future studies should focus on updating bibliomet-

ric analyses, integrating multidisciplinary approaches, exploring hybrid construction innovations, and enhancing fire safety research to align with industry standards and regulatory frameworks.

5. Final remarks: This study contributes to a deeper understanding of how mid- and high-rise timber buildings have evolved as a research field. Future research should aim to bridge the gap between sustainability, structural performance, and societal perceptions to maximize the benefits of timber construction in urban contexts.

Author Contributions: Conceptualization, A.W., P.G. and M.C.; methodology, A.W., P.G. and M.C.; software, A.W., P.G. and M.C.; validation, P.G. and M.C.; formal analysis, A.W., P.G. and M.C.; investigation, A.W., P.G. and M.C.; resources, A.W., P.G. and M.C.; writing—original draft preparation, A.W., P.G. and M.C.; supervision, P.G. and M.C.; funding acquisition, P.G. and M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the projects ANID BASAL FB210015 CENAMAD; BG23/00134; and the Pontificia Universidad Católica de Chile through the 2024 International Sabbatical Support Competition of the Academic Vice-Rectorship.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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

References

1. Al-Kodmany, K. Sustainable High-Rise Buildings: Toward Resilient Built Environment. *Front. Sustain. Cities* **2022**, *4*, 782007. [CrossRef]
2. Ali, M.M.; Al-Kodmany, K. Tall Buildings and Urban Habitat of the 21st Century: A Global Perspective. *Buildings* **2012**, *2*, 384–423. [CrossRef]
3. Mostafavi, F.; Tahsildoost, M.; Zomorodian, Z.S. Energy Efficiency and Carbon Emission in High-Rise Buildings: A Review (2005–2020). *Build. Environ.* **2021**, *206*, 108329. [CrossRef]
4. Robati, M.; Oldfield, P. The Embodied Carbon of Mass Timber and Concrete Buildings in Australia: An Uncertainty Analysis. *Build. Environ.* **2022**, *214*, 108944. [CrossRef]
5. Mishra, A.; Humpenöder, F.; Churkina, G.; Reyer, C.P.O.; Beier, F.; Bodirsky, B.L.; Schellnhuber, H.J.; Lotze-Campen, H.; Popp, A. Land Use Change and Carbon Emissions of a Transformation to Timber Cities. *Nat. Commun.* **2022**, *13*, 4889. [CrossRef]
6. UNECE. *The Outlook for the Unece Forest Sector in a Changing Climate; A Contribution to the Forest Sector Outlook Study 2020–2040*; United Nations: New York, NY, USA, 2022; ISBN 9789210023733.
7. Svatoš-Ražnjević, H.; Orozco, L.; Menges, A. Advanced Timber Construction Industry: A Review of 350 Multi-Storey Timber Projects from 2000–2021. *Buildings* **2022**, *12*, 404. [CrossRef]
8. Fuglsang Nielsen, L. Lifetime, Residual Strength, and Quality of Wood and Other Viscoelastic Building Materials. *Holz Als Roh-Und Werkst.* **1991**, *49*, 451–455. [CrossRef]
9. Sheffield, J.W.; Barbera, J.J. The 1991 Uniform Building Code Wind Load Provisions. *J. Wind. Eng. Ind. Aerodyn.* **1992**, *44*, 2921–2932. [CrossRef]
10. Villaverde, R.; Koyama, L.A. Damped Resonant Appendages to Increase Inherent Damping in Buildings. *Eng. Struct. Dyn.* **1993**, *22*, 491–507. [CrossRef]
11. González-Retamal, M.; Forcael, E.; Saelzer-Fuica, G.; Vargas-Mosqueda, M. From Trees to Skyscrapers: Holistic Review of the Advances and Limitations of Multi-Storey Timber Buildings. *Buildings* **2022**, *12*, 1263. [CrossRef]
12. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to Conduct a Bibliometric Analysis: An Overview and Guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [CrossRef]
13. Han, J.; Kang, H.J.; Kim, M.; Kwon, G.H. Mapping the Intellectual Structure of Research on Surgery with Mixed Reality: Bibliometric Network Analysis (2000–2019). *J. Biomed. Inform.* **2020**, *109*, 103516. [CrossRef] [PubMed]
14. Silva, T.C.; Araujo, E.C.G.; da Silva Lins, T.R.; Reis, C.A.; Sanquetta, C.R.; da Rocha, M.P. Non-Timber Forest Products in Brazil: A Bibliometric and a State of the Art Review. *Sustainability* **2020**, *12*, 7151. [CrossRef]

15. Abejón, R.; Moya, L. Cross-Laminated Timber: Perspectives from a Bibliometric Analysis (2006–2018). *Wood Mater. Sci. Eng.* **2021**, *17*, 429–450. [CrossRef]
16. Pyzhev, A.I. Studies on the Russian Forest Industry: Bibliometric Analysis. *Terra Econ.* **2021**, *19*, 63–77. [CrossRef]
17. Rodríguez-Grau, G.; Marín-Uribe, C.; Cortés-Rodríguez, P.; Montero, C.; Rosales, V.; Galarce, C. Bibliometric Analysis of the Green Gluing Technique (2000–2020): Trends and Perspectives. *Forests* **2022**, *13*, 1714. [CrossRef]
18. De Iuliis, M.; Cardoni, A.; Paolo Cimellaro, G. Resilience and Safety of Civil Engineering Systems and Communities: A Bibliometric Analysis for Mapping the State-of-the-Art. *Saf. Sci.* **2024**, *174*, 106470. [CrossRef]
19. Mahapatra, K.; Gustavsson, L. Multi-Storey Timber Buildings: Breaking Industry Path Dependency. *Build. Res. Inf.* **2008**, *36*, 638–648. [CrossRef]
20. Dodoo, A.; Gustavsson, L.; Sathre, R. Lifecycle Carbon Implications of Conventional and Low-Energy Multi-Storey Timber Building Systems. *Energy Build.* **2014**, *82*, 194–210. [CrossRef]
21. Berwart, S.; Estrella, X.; Montaño, J.; Santa-María, H.; Almazán, J.L.; Guindos, P. A Simplified Approach to Assess the Technical Prefeasibility of Multistory Wood-Frame Buildings in High Seismic Zones. *Eng. Struct.* **2022**, *257*, 114035. [CrossRef]
22. Lazzarini, E.; Frison, G.; Trutalli, D.; Marchi, L.; Scotta, R. Comfort Assessment of High-Rise Timber Buildings Exposed to Wind-Induced Vibrations. *Struct. Des. Tall Spec. Build.* **2021**, *30*, e1882. [CrossRef]
23. Cobo, M.J.; López-Herrera, A.G.; Herrera-Viedma, E.; Herrera, F. An Approach for Detecting, Quantifying, and Visualizing the Evolution of a Research Field: A Practical Application to the Fuzzy Sets Theory Field. *J. Informetr.* **2011**, *5*, 146–166. [CrossRef]
24. Cobo, M.J.; Lõpez-Herrera, A.G.; Herrera-Viedma, E.; Herrera, F. SciMAT: A New Science Mapping Analysis Software Tool. *J. Am. Soc. Inf. Sci. Technol.* **2012**, *63*, 1609–1630. [CrossRef]
25. Díaz-López, C.; Carpio, M.; Martín-Morales, M.; Zamorano, M. Analysis of the Scientific Evolution of Sustainable Building Assessment Methods. *Sustain. Cities Soc.* **2019**, *49*, 101610. [CrossRef]
26. Heradio, R.; De La Torre, L.; Galan, D.; Cabrerizo, F.J.; Herrera-Viedma, E.; Dormido, S. Virtual and Remote Labs in Education: A Bibliometric Analysis. *Comput. Educ.* **2016**, *98*, 14–38. [CrossRef]
27. Callon, M.; Courtial, J.P.; Laville, F. Co-Word Analysis as a Tool for Describing the Network of Interactions between Basic and Technological Research: The Case of Polymer Chemsitry. *Scientometrics* **1991**, *22*, 155–205. [CrossRef]
28. Petković, M.; Škrlj, B.; Kocev, D.; Simidjievski, N. Fuzzy Jaccard Index: A Robust Comparison of Ordered Lists [Formula Presented]. *Appl. Soft Comput.* **2021**, *113*, 107849. [CrossRef]
29. Van Eck, N.J.; Waltman, L. How to Normalize Cooccurrence Data? An Analysis of Some Well-Known Similarity Measures. *J. Am. Soc. Inf. Sci. Technol.* **2009**, *60*, 1635–1651. [CrossRef]
30. Nalbandian, K.M.; Carpio, M.; González, Á. Analysis of the Scientific Evolution of Self-Healing Asphalt Pavements: Toward Sustainable Road Materials. *J. Clean. Prod.* **2021**, *293*, 126107. [CrossRef]
31. Santana, M.; Cobo, M.J. What Is the Future of Work? A Science Mapping Analysis. *Eur. Manag. J.* **2020**, *38*, 846–862. [CrossRef]
32. Börjesson, P.K.; Gustavsson, L. Greenhouse Gas Balances in Building Construction: Wood versus Concrete from Life-Cycle and Forest Land-Use Perspectives. *Energy Policy* **2000**, *28*, 575–588. [CrossRef]
33. Werner, F.; Richter, K. Wooden Building Products in Comparative LCA: A Literature Review. *Int. J. Life Cycle Assess.* **2007**, *12*, 470–479. [CrossRef]
34. Puettmann, M.E.; Associate, R.; Wilson, J.B. Life-Cycle Analysis of Wood Products: Cradle-to-Gate Lci of Residential Wood Building Materials. *Wood Fiber Sci.* **2006**, *37*, 18–29.
35. Werner, F.; Taverna, R.; Hofer, P.; Richter, K. Carbon Pool and Substitution Effects of an Increased Use of Wood in Buildings in Switzerland: First Estimates. *Ann. For. Sci.* **2005**, *62*, 889–902. [CrossRef]
36. Werner, F.; Taverna, R.; Hofer, P.; Richter, K. Greenhouse Gas Dynamics of an Increased Use of Wood in Buildings in Switzerland. *Clim. Change* **2006**, *74*, 319–347. [CrossRef]
37. Pei, S.; van de Lindt, J.W. Coupled Shear-Bending Formulation for Seismic Analysis of Stacked Wood Shear Wall Systems. *Earthq. Eng. Struct. Dyn.* **2009**, *38*, 1631–1647. [CrossRef]
38. Kilpeläinen, M.; Ukonmaanaho, A. Panelized Building System for Multi-Storey Timber Frame Houses. *IABSE Symp. Rep.* **2001**, *85*, 37–42.
39. van de Lindt, J.; Dao, T. Construction Quality Issues in Performance-Based Wind Engineering: Effect of Missing Fasteners. *Wind. Struct.* **2010**, *13*, 221–234. [CrossRef]
40. Mosalam, K.M.; Mahin, S.A. Seismic Evaluation and Retrofit of Asymmetric Multi-Story Wood-Frame Building. *J. Earthq. Eng.* **2007**, *11*, 968–986. [CrossRef]
41. Langlois, J.D.; Gupta, R.; Asce, M.; Miller, T.H. Effects of Reference Displacement and Damage Accumulation in Wood Shear Walls. *J. Struct. Eng.* **2004**, *130*, 470–479. [CrossRef]
42. Ceccotti, A.; Sandhaas, C.; Okabe, M.; Yasumura, M.; Minowa, C.; Kawai, N. SOFIE Project—3D Shaking Table Test on a Seven-Storey Full-Scale Cross-Laminated Timber Building. *Earthq. Eng. Struct. Dyn.* **2013**, *42*, 2003–2021. [CrossRef]

43. Fragiacomo, M.; Dujic, B.; Sustersic, I. Elastic and Ductile Design of Multi-Storey Crosslam Massive Wooden Buildings under Seismic Actions. *Eng. Struct.* **2011**, *33*, 3043–3053. [CrossRef]
44. Salvadori, V. *Multi-Storey Timber-Based Buildings: An International Survey of Case-Studies with Five or More Storeys Over the Last Twenty Years*; Technische Universität Wien: Vienna, Austria, 2021.
45. Guindos, P. *Fundamentos Del Diseño y La Construcción Con Madera*; Ediciones UC: Santiago, Chile, 2019; Volume I.
46. Liu, Y.; Guo, H.; Sun, C.; Chang, W.S. Assessing Cross Laminated Timber (CLT) as an Alternative Material for Mid-Rise Residential Buildings in Cold Regions in China-A Life-Cycle Assessment Approach. *Sustainability* **2016**, *8*, 1047. [CrossRef]
47. Dodoo, A.; Gustavsson, L.; Sathre, R. Lifecycle Primary Energy Analysis of Low-Energy Timber Building Systems for Multi-Storey Residential Buildings. *Energy Build.* **2014**, *81*, 84–97. [CrossRef]
48. Skullestad, J.L.; Bohne, R.A.; Lohne, J. High-Rise Timber Buildings as a Climate Change Mitigation Measure—A Comparative LCA of Structural System Alternatives. *Energy Procedia* **2016**, *96*, 112–123. [CrossRef]
49. Hossaini, N.; Reza, B.; Akhtar, S.; Sadiq, R.; Hewage, K. AHP Based Life Cycle Sustainability Assessment (LCSA) Framework: A Case Study of Six Storey Wood Frame and Concrete Frame Buildings in Vancouver. *J. Environ. Plan. Manag.* **2015**, *58*, 1217–1241. [CrossRef]
50. Tettey, U.Y.A.; Dodoo, A.; Gustavsson, L. Effects of Different Insulation Materials on Primary Energy and CO_2 Emission of a Multi-Storey Residential Building. *Energy Build.* **2014**, *82*, 369–377. [CrossRef]
51. Erdle, A.; Weckendorf, J.; Asiz, A.; Smith, I. Effectiveness of Distributed Mass Damper Systems for Lightweight Superstructures. *J. Perform. Constr. Facil.* **2014**, *28*, A4014005. [CrossRef]
52. Foster, R.M.; Reynolds, T.P.S.; Ramage, M.H. Proposal for Defining a Tall Timber Building. *J. Struct. Eng.* **2016**, *142*, 02516001. [CrossRef]
53. Churkina, G.; Organschi, A.; Reyer, C.P.O.; Ruff, A.; Vinke, K.; Liu, Z.; Reck, B.K.; Graedel, T.E.; Schellnhuber, H.J. Buildings as a Global Carbon Sink. *Nat. Sustain.* **2020**, *3*, 269–276. [CrossRef]
54. Asdrubali, F.; Ferracuti, B.; Lombardi, L.; Guattari, C.; Evangelisti, L.; Grazieschi, G. A Review of Structural, Thermo-Physical, Acoustical, and Environmental Properties of Wooden Materials for Building Applications. *Build. Environ.* **2017**, *114*, 307–332. [CrossRef]
55. Bartlett, A.I.; Hadden, R.M.; Bisby, L.A. A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction. *Fire Technol.* **2019**, *55*, 1–49. [CrossRef]
56. Mpidi Bita, H.; Tannert, T. Experimental Study of Disproportionate Collapse Prevention Mechanisms for Mass-Timber Floor Systems. *J. Struct. Eng.* **2020**, *146*, 04019199. [CrossRef]
57. Mpidi Bita, H.; Currie, N.; Tannert, T. Disproportionate Collapse Analysis of Mid-Rise Cross-Laminated Timber Buildings. *Struct. Infrastruct. Eng.* **2018**, *14*, 1547–1560. [CrossRef]
58. Mpidi Bita, H.; Tannert, T. Disproportionate Collapse Prevention Analysis for a Mid-Rise Flat-Plate Cross-Laminated Timber Building. *Eng. Struct.* **2019**, *178*, 460–471. [CrossRef]
59. Huber, J.A.J.; Ekevad, M.; Girhammar, U.A.; Berg, S. Structural Robustness and Timber Buildings—A Review. *Wood Mater. Sci. Eng.* **2019**, *14*, 107–128. [CrossRef]
60. Mpidi Bita, H.; Tannert, T. Tie-Force Procedure for Disproportionate Collapse Prevention of CLT Platform-Type Construction. *Eng. Struct.* **2019**, *189*, 195–205. [CrossRef]
61. Huber, J.A.J.; Mpidi Bita, H.; Tannert, T.; Berg, S. Finite Element Analysis of Alternative Load Paths to Prevent Disproportionate Collapse in Platform-Type CLT Floor Systems. *Eng. Struct.* **2021**, *240*, 112362. [CrossRef]
62. Alih, S.C.; Vafaei, M. Performance of Reinforced Concrete Buildings and Wooden Structures during the 2015 Mw 6.0 Sabah Earthquake in Malaysia. *Eng. Fail. Anal.* **2019**, *102*, 351–368. [CrossRef]
63. Pina, J.C.; Saavedra Flores, E.I.; Saavedra, K. Numerical Study on the Elastic Buckling of Cross-Laminated Timber Walls Subject to Compression. *Constr. Build. Mater.* **2019**, *199*, 82–91. [CrossRef]
64. Escamilla, E.Z.; Habert, G.; Daza, J.F.C.; Archilla, H.F.; Echeverry Fernández, J.S.; Trujillo, D. Industrial or Traditional Bamboo Construction? Comparative Life Cycle Assessment (LCA) of Bamboo-Based Buildings. *Sustainability* **2018**, *10*, 3096. [CrossRef]
65. Padilla-Rivera, A.; Amor, B.; Blanchet, P. Evaluating the Link between Low Carbon Reductions Strategies and Its Performance in the Context of Climate Change: A Carbon Footprint of Awood-Frame Residential Building in Quebec, Canada. *Sustainability* **2018**, *10*, 2715. [CrossRef]
66. Bahramian, M.; Yetilmezsoy, K. Life Cycle Assessment of the Building Industry: An Overview of Two Decades of Research (1995–2018). *Energy Build.* **2020**, *219*, 109917. [CrossRef]
67. Jayalath, A.; Navaratnam, S.; Ngo, T.; Mendis, P.; Hewson, N.; Aye, L. Life Cycle Performance of Cross Laminated Timber Mid-Rise Residential Buildings in Australia. *Energy Build.* **2020**, *223*, 110091. [CrossRef]
68. Li, J.; Rismanchi, B.; Ngo, T. Feasibility Study to Estimate the Environmental Benefits of Utilising Timber to Construct High-Rise Buildings in Australia. *Build. Environ.* **2019**, *147*, 108–120. [CrossRef]

69. Tettey, U.Y.A.; Dodoo, A.; Gustavsson, L. Effect of Different Frame Materials on the Primary Energy Use of a Multi Storey Residential Building in a Life Cycle Perspective. *Energy Build.* **2019**, *185*, 259–271. [CrossRef]
70. Bruno, R.; Bevilacqua, P.; Cuconati, T.; Arcuri, N. Energy Evaluations of an Innovative Multi-Storey Wooden near Zero Energy Building Designed for Mediterranean Areas. *Appl. Energy* **2019**, *238*, 929–941. [CrossRef]
71. Markström, E.; Kitek Kuzman, M.; Bystedt, A.; Sandberg, D. Use of Wood Products in Multi-Storey Residential Buildings: Views of Swedish Actors and Suggested Measures for an Increased Use. *Wood Mater. Sci. Eng.* **2019**, *14*, 404–419. [CrossRef]
72. Gosselin, A.; Blanchet, P.; Lehoux, N.; Cimon, Y. Main Motivations and Barriers for Using Wood in Multi-Story and Non-Residential Construction Projects. *BioResources* **2017**, *12*, 546–570. [CrossRef]
73. Markström, E.; Kuzman, M.K.; Bystedt, A.; Sandberg, D.; Fredriksson, M. Swedish Architects View of Engineered Wood Products in Buildings. *J. Clean. Prod.* **2018**, *181*, 33–41. [CrossRef]
74. Riggio, M.; Alhariri, N.; Hansen, E. Paths of Innovation and Knowledge Management in Timber Construction in North America: A Focus on Water Control Design Strategies in CLT Building Enclosures. *Archit. Eng. Des. Manag.* **2020**, *16*, 58–83. [CrossRef]
75. Lu, H.R.; El Hanandeh, A.; Gilbert, B.P. A Comparative Life Cycle Study of Alternative Materials for Australian Multi-Storey Apartment Building Frame Constructions: Environmental and Economic Perspective. *J. Clean. Prod.* **2017**, *166*, 458–473. [CrossRef]
76. Himes, A.; Busby, G. Wood Buildings as a Climate Solution. *Dev. Built Environ.* **2020**, *4*, 100030. [CrossRef]
77. Dodoo, A.; Gustavsson, L. Energy Use and Overheating Risk of Swedish Multi-Storey Residential Buildings under Different Climate Scenarios. *Energy* **2016**, *97*, 534–548. [CrossRef]
78. Vidal, R.; Sánchez-Pantoja, N.; Martínez, G. Life Cycle Assessment of a Residential Building with Cross-Laminated Timber Structure in Granada-Spain. *Inf. De La Constr.* **2019**, *71*, 289. [CrossRef]
79. Leskovar, V.Ž.; Žigart, M.; Premrov, M.; Lukman, R.K. Comparative Assessment of Shape Related Cross-Laminated Timber Building Typologies Focusing on Environmental Performance. *J. Clean. Prod.* **2019**, *216*, 482–494. [CrossRef]
80. Gustavsson, L.; Nguyen, T.; Sathre, R.; Tettey, U.Y.A. Climate Effects of Forestry and Substitution of Concrete Buildings and Fossil Energy. *Renew. Sustain. Energy Rev.* **2021**, *136*, 110435. [CrossRef]
81. Aloisio, A.; Alaggio, R.; Fragiacomo, M. Fragility Functions and Behavior Factors Estimation of Multi-Story Cross-Laminated Timber Structures Characterized by an Energy-Dependent Hysteretic Model. *Earthq. Spectra* **2021**, *37*, 134–159. [CrossRef]
82. Xia, R.; Zhang, W.; Yang, Y.; Zhao, J.; Liu, Y.; Guo, H. Transparent Wood with Phase Change Heat Storage as Novel Green Energy Storage Composites for Building Energy Conservation. *J. Clean. Prod.* **2021**, *296*, 126598. [CrossRef]
83. Piccardo, C.; Gustavsson, L. Implications of Different Modelling Choices in Primary Energy and Carbon Emission Analysis of Buildings. *Energy Build.* **2021**, *247*, 111145. [CrossRef]
84. Myllyviita, T.; Hurmekoski, E.; Kunttu, J. Substitution Impacts of Nordic Wood-Based Multi-Story Building Types: Influence of the Decarbonization of the Energy Sector and Increased Recycling of Construction Materials. *Carbon. Balance Manag.* **2022**, *17*, 4. [CrossRef] [PubMed]
85. Amoruso, F.M.; Schuetze, T. Life Cycle Assessment and Costing of Carbon Neutral Hybrid-Timber Building Renovation Systems: Three Applications in the Republic of Korea. *Build. Environ.* **2022**, *222*, 109395. [CrossRef]
86. Younis, A.; Dodoo, A. Cross-Laminated Timber for Building Construction: A Life-Cycle-Assessment Overview. *J. Build. Eng.* **2022**, *52*, 104482. [CrossRef]
87. Karjalainen, M.; Ilgın, H.E.; Tulonen, L. Main Design Considerations and Prospects of Contemporary Tall Timber Apartment Buildings: Views of Key Professionals from Finland. *Sustainability* **2021**, *13*, 6593. [CrossRef]
88. Ilgın, H.E.; Karjalainen, M.; Pelsmakers, S. Finnish Architects' Attitudes towards Multi-Storey Timber-Residential Buildings. *Int. J. Build. Pathol. Adapt.* **2021**, *42*, 352–368. [CrossRef]
89. Toivonen, R.; Vihemäki, H.; Toppinen, A. Policy Narratives on Wooden Multi-Storey Construction and Implications for Technology Innovation System Governance. *For. Policy Econ.* **2021**, *125*, 102409. [CrossRef]
90. Viholainen, N.; Franzini, F.; Lähtinen, K.; Nyrud, A.Q.; Widmark, C.; Hoen, H.F.; Toppinen, A. Citizen Views on Wood as a Construction Material: Results from Seven European Countries. *Can. J. For. Res.* **2021**, *51*, 647–659. [CrossRef]
91. Nagy, E.; Berg Rustas, C.; Mark-Herbert, C. Social Acceptance of Forest-Based Bioeconomy—Swedish Consumers' Perspectives on a Low Carbon Transition. *Sustainability* **2021**, *13*, 7628. [CrossRef]
92. Giorgio, B.; Blanchet, P.; Barlet, A. Social Representations of Mass Timber and Prefabricated Light-Frame Wood Construction for Multi-Story Housing: The Vision of Users in Quebec. *Buildings* **2022**, *12*, 2073. [CrossRef]
93. Karjalainen, M.; Ilgın, H.E. The Change over Time in Finnish Residents' Attitudes towards Multi-Story Timber Apartment Buildings. *Sustainability* **2021**, *13*, 5501. [CrossRef]
94. Allan, K.; Phillips, A.R. Comparative Cradle-to-Grave Life Cycle Assessment of Low and Mid-Rise Mass Timber Buildings with Equivalent Structural Steel Alternatives. *Sustainability* **2021**, *13*, 3401. [CrossRef]
95. Chaggaris, R.; Pei, S.; Kingsley, G.; Feitel, A. Carbon Impact and Cost of Mass Timber Beam–Column Gravity Systems. *Sustainability* **2021**, *13*, 12966. [CrossRef]

96. Peñaloza, D.; Erlandsson, M.; Falk, A. Exploring the Climate Impact Effects of Increased Use of Bio-Based Materials in Buildings. *Constr. Build. Mater.* **2016**, *125*, 219–226. [CrossRef]
97. Andersen, J.H.; Rasmussen, N.L.; Ryberg, M.W. Comparative Life Cycle Assessment of Cross Laminated Timber Building and Concrete Building with Special Focus on Biogenic Carbon. *Energy Build.* **2022**, *254*, 111604. [CrossRef]
98. Hawkins, W.; Cooper, S.; Allen, S.; Roynon, J.; Ibell, T. Embodied Carbon Assessment Using a Dynamic Climate Model: Case-Study Comparison of a Concrete, Steel and Timber Building Structure. *Structures* **2021**, *33*, 90–98. [CrossRef]
99. Bezabeh, M.A.; Bitsuamlak, G.T.; Popovski, M.; Tesfamariam, S. Probabilistic Serviceability-Performance Assessment of Tall Mass-Timber Buildings Subjected to Stochastic Wind Loads: Part I—Structural Design and Wind Tunnel Testing. *J. Wind Eng. Ind. Aerodyn.* **2018**, *181*, 85–103. [CrossRef]
100. Bezabeh, M.A.; Bitsuamlak, G.T.; Popovski, M.; Tesfamariam, S. Probabilistic Serviceability-Performance Assessment of Tall Mass-Timber Buildings Subjected to Stochastic Wind Loads: Part II—Structural Reliability Analysis. *J. Wind. Eng. Ind. Aerodyn.* **2018**, *181*, 112–125. [CrossRef]
101. Roueche, D.B.; Prevatt, D.O.; Haan, F.L.; Datin, P.L. An Estimate of Tornado Loads on a Wood-Frame Building Using Database-Assisted Design Methodology. *J. Wind. Eng. Ind. Aerodyn.* **2015**, *138*, 27–35. [CrossRef]
102. Edskär, I.; Lidelöw, H. Dynamic Properties of Cross-Laminated Timber and Timber Truss Building Systems. *Eng. Struct.* **2019**, *186*, 525–535. [CrossRef]
103. Tannert, T.; Connolly, T.J. Hybrides Tragwerk Des 18-Stöckigen Studentenwohnheims "Tall Wood Building" in Vancouver Und Alternative in Holz. *Bautechnik* **2020**, *97*, 56–63. [CrossRef]
104. Binck, C.; Cao, A.S.; Frangi, A. Lateral Stiffening Systems for Tall Timber Buildings–Tube-in-Tube Systems. *Wood Mater. Sci. Eng.* **2022**, *17*, 309–316. [CrossRef]
105. Cao, A.S.; Stamatopoulos, H. A Theoretical Study of the Dynamic Response of Planar Timber Frames with Semi-Rigid Moment-Resisting Connections Subjected to Wind Loads. *Eng. Struct.* **2021**, *240*, 112367. [CrossRef]
106. Zhao, X.; Zhang, B.; Kilpatrick, T.; Sanderson, I. Numerical Analysis on Global Serviceability Behaviours of Tall Clt Buildings to the Eurocodes and Uk National Annexes. *Buildings* **2021**, *11*, 124. [CrossRef]
107. Voulpiotis, K.; Schär, S.; Frangi, A. Quantifying Robustness in Tall Timber Buildings: A Case Study. *Eng. Struct.* **2022**, *265*, 114427. [CrossRef]
108. Lyu, C.H.; Gilbert, B.P.; Guan, H.; Underhill, I.D.; Gunalan, S.; Karampour, H. Experimental Study on the Quasi-Static Progressive Collapse Response of Post-and-Beam Mass Timber Buildings under an Edge Column Removal Scenario. *Eng. Struct.* **2021**, *228*, 111425. [CrossRef]
109. Voulpiotis, K.; Köhler, J.; Jockwer, R.; Frangi, A. A Holistic Framework for Designing for Structural Robustness in Tall Timber Buildings. *Eng. Struct.* **2021**, *227*, 111432. [CrossRef]
110. Xia, Z.; Van De Kuilen, J.W.G.; Polastri, A.; Ceccotti, A.; He, M. Influence of Core Stiffness on the Behavior of Tall Timber Buildings Subjected to Wind Loads. *Front. Struct. Civ. Eng.* **2021**, *15*, 213–226. [CrossRef]
111. Chen, J.; Xiong, H.; Ventura, C.E. Non-Linear Simplified Models for Seismic Response Estimation of a Novel Tall Timber-Concrete Hybrid Structural System. *Eng. Struct.* **2021**, *229*, 111635. [CrossRef]
112. Navaratnam, S.; Widdowfield Small, D.; Gatheeshgar, P.; Poologanathan, K.; Thamboo, J.; Higgins, C.; Mendis, P. Development of Cross Laminated Timber-Cold-Formed Steel Composite Beam for Floor System to Sustainable Modular Building Construction. *Structures* **2021**, *32*, 681–690. [CrossRef]
113. Rinaldi, V.; Casagrande, D.; Cimini, C.; Follesa, M.; Fragiacomo, M. An Upgrade of Existing Practice-Oriented FE Design Models for the Seismic Analysis of CLT Buildings. *Soil Dyn. Earthq. Eng.* **2021**, *149*, 106802. [CrossRef]
114. Labrecque, N.; Ménard, S.; Oudjene, M.; Blanchet, P. Finite Element Study of Hyperstructure Systems with Modular Light-Frame Construction in High-Rise Buildings. *Buildings* **2022**, *12*, 330. [CrossRef]
115. Shameli Derakhshan, S.; Ni, C.; Zhou, L.; Qiang, R.; Huang, D. Cyclic Test and Seismic Equivalency Evaluation of High-Capacity Light Wood-Frame Shear Walls for Midrise Buildings. *J. Struct. Eng.* **2022**, *148*, 04022168. [CrossRef]
116. Wenzel, A.; Vera, S.; Guindos, P. Integration of Energy and Seismic-Structural Design Variables through the Optimization of a Multi-Story Residential Light-Frame Timber Building with Different Seismic Lateral Connectors and Building Stories. *J. Build. Eng.* **2022**, *57*, 104831. [CrossRef]
117. Dimovska, S.; Saloustros, S.; Pelà, L.; Roca, P. Modelling of In-Plane Seismic Behaviour of One-Way Steel or Timber Jack Arch Floors in Existing Buildings. Application to the Eixample District of Barcelona. *Eng. Struct.* **2022**, *262*, 114343. [CrossRef]
118. Carrero, T.; Montaño, J.; Berwart, S.; Santa María, H.; Guindos, P. Seismic Behavior of Innovative Hybrid CLT-Steel Shear Wall for Mid-Rise Buildings. *Bull. Earthq. Eng.* **2021**, *19*, 5917–5951. [CrossRef]
119. Movaffaghi, H.; Yitmen, I. Multi-Criteria Decision Analysis of Timber–Concrete Composite Floor Systems in Multi-Storey Wooden Buildings. *Civ. Eng. Environ. Syst.* **2021**, *38*, 161–175. [CrossRef]
120. Julien, E.; Blanchet, P.; Gosselin, L. Case-Study: Fully Prefabricated Wood Wall Connection to Improve Building Envelope and On-Site Efficiency. *Buildings* **2022**, *12*, 2185. [CrossRef]

121. Gibson, B.; Nguyen, T.; Sinaie, S.; Heath, D.; Ngo, T. The Low Frequency Structure-Borne Sound Problem in Multi-Storey Timber Buildings and Potential of Acoustic Metamaterials: A Review. *Build. Environ.* **2022**, *224*, 109531. [CrossRef]
122. Amoruso, F.M.; Schuetze, T. Hybrid Timber-Based Systems for Low-Carbon, Deep Renovation of Aged Buildings: Three Exemplary Buildings in the Republic of Korea. *Build. Environ.* **2022**, *214*, 108889. [CrossRef]
123. Bajno, D.; Grzybowska, A.; Bednarz, Ł. Old and Modern Wooden Buildings in the Context of Sustainable Development. *Energies* **2021**, *14*, 5975. [CrossRef]
124. Ouellet-Plamondon, C.M.; Ramseier, L.; Balouktsi, M.; Delem, L.; Foliente, G.; Francart, N.; Garcia-Martinez, A.; Hoxha, E.; Lützkendorf, T.; Nygaard Rasmussen, F.; et al. Carbon Footprint Assessment of a Wood Multi-Residential Building Considering Biogenic Carbon. *J. Clean. Prod.* **2023**, *404*, 136834. [CrossRef]
125. Tung, S.-F.; Su, H.-C.; Tzeng, C.-T.; Lai, C.-M. Experimental and Numerical Investigation of a Room Fire in a Wooden-Frame Historical Building. *Int. J. Archit. Herit.* **2020**, *14*, 106–118. [CrossRef]
126. Huai, C.; Xie, J.; Liu, F.; Liu, J. Study on the Thermal Stability and Degradation Kinetics of the Historical Wood: Restoration Residues Collected from Chinese Heritage Buildings. *Int. J. Arch. Heritage* **2022**, *18*, 164–176. [CrossRef]
127. Létourneau-Gagnon, M.; Dagenais, C.; Blanchet, P. Fire Performance of Self-Tapping Screws in Tall Mass-Timber Buildings. *Appl. Sci.* **2021**, *11*, 3579. [CrossRef]
128. Zhang, L.; Chen, K.; Liu, W.; Liu, Y.; Wang, K.; Ge, W.; Guo, K. Fire Performance of Pultruded Wood-Cored GFRP Sandwich Components for Building Construction. *Case Stud. Constr. Mater.* **2022**, *17*, e01555. [CrossRef]
129. Engel, T.; Werther, N. Impact of Mass Timber Compartment Fires on Façade Fire Exposure. *Fire Technol.* **2023**, *59*, 517–558. [CrossRef]
130. Sudhoff, P.; Steeger, F.; Zehfuß, J.; Kampmeier, B. Fire Performance of Insulating Materials Made from Renewable Resources—Part 2: Investigations on the Use as Compartment Filling in Timber Panel Constructions. *Bauphysik* **2021**, *43*, 303–313. [CrossRef]
131. Steeger, F.; Kolb, T.; Tech, S.; Wichmann, H.; Kampmeier, B.; Zehfuß, J.; Kolb, M. Fire Performance of Insulating Materials Made from Renewable Resources—Part 1: Experimental Investigations of -Smouldering Processes and Emissions. *Bauphysik* **2021**, *43*, 222–230. [CrossRef]
132. Bahrami, A.; Edås, M.; Magnenat, K.; Norén, J. The Behavior of Cross-Laminated Timber and Reinforced Concrete Floors in a Multi-Story Building. *Int. J. Adv. Appl. Sci.* **2022**, *9*, 43–50. [CrossRef]
133. Engel, T.; Moosmüller, K.; Werther, N. Fire Hazard Due to Electrical Installations in Modern Multi-Storey Timber Buildings. *Bautechnik* **2021**, *98*, 353–364. [CrossRef]
134. Bucklin, O.; Müller, T.; Amtsberg, F.; Leistner, P.; Menges, A. Analysis of Thermal Transmittance, Air Permeability, and Hygrothermal Behavior of a Solid Timber Building Envelope. *Energy Build.* **2023**, *299*, 113629. [CrossRef]
135. Lauer, A.P.R.; Benner, E.; Stark, T.; Klassen, S.; Abolhasani, S.; Schroth, L.; Gienger, A.; Wagner, H.J.; Schwieger, V.; Menges, A.; et al. Automated On-Site Assembly of Timber Buildings on the Example of a Biomimetic Shell. *Autom. Constr.* **2023**, *156*, 105118. [CrossRef]
136. Öberg, V.; Jockwer, R.; Goto, Y. Design for Structural Adaptation in Timber Buildings: Industry Perspectives and Implementation Roadmap for Sweden and Australia. *J. Build. Eng.* **2024**, *98*, 111413. [CrossRef]
137. Liu, H.; Wu, Y.; Li, A.; Deng, Y. Precision Detection and Identification Method for Apparent Damage in Timber Components of Historic Buildings Based on Portable LiDAR Equipment. *J. Build. Eng.* **2024**, *98*, 111050. [CrossRef]