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Review

Bibliometric Review of Prefabricated and Modular Timber Construction from 1990 to 2023: Evolution, Trends, and Current Challenges

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Abstract: Due to its inherent characteristics, such as a light weight and ease of workability, timber is ideal for prefabricated and modular construction. However, since the research in this field covers a wide range of niches such as structural engineering, building physics, design for assembly and disassembly, and life cycle analysis, among others, and since there has been considerable development of the field in past years—boosted by new mass timber products and tall timber construction—it is difficult to critically analyze the current state of the art, current trends, and research challenges. Therefore, this research aimed to cover a systematic review of 409 articles to assess the field of prefabricated and modular timber construction critically. The methodology comprised a co-word network approach using the Science Mapping Analysis Software Tool (SciMAT, Version 3) to illustrate their evolution from 1990 to 2023. The findings show that the circular economy and digital technologies significantly impact the development of these technologies, which can potentially provide practical solutions for designing buildings with a circular approach and improving productivity and efficiency in the construction process. However, it is essential to acknowledge a notable deficiency in the research and understanding of these subjects. Therefore, various sectors must take the lead in conducting a thorough reassessment to enhance research and development in the field. Finally, the findings from this research can significantly contribute to existing knowledge and serve as a comprehensive platform for the further exploration of prefabricated and modular timber construction.

Keywords: prefabrication; modular timber construction; circular economy; digital technologies

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1. Introduction

Off-site construction, also commonly referred to as prefabrication, involves manufacturing various structural components within a controlled factory environment, subsequently facilitating the transportation of complete assemblies or subassemblies to the designated construction site where the intended structure is to be established [1]. Modular construction is widely recognized as a fundamental approach within offsite construction [2]. This technology can achieve a remarkable level of completion, reaching upwards of 95% before its transportation to the designated location [1]. While some researchers state that modular construction is constituted by a dimensionally unified spatial unit or a 3D volumetric section [3–6], others describe it in the form of 2D planar components (pre-assembled elements) or fully volumetric units [7–9]. From the viewpoint of these authors, modules can cover a diverse range of prefabricated elements or systems, including component groups and complete units of significant size and volume.

These two approaches will be appropriate depending on the demands of each project. The assembly work involved in a 2D panelized system is intricate due to its requirement for additional internal finishing. Nevertheless, it provides superior flexibility. In contrast, volumetric units require adaptation to building specifications, which demands early involvement in the design process to ensure the desired result. Still, it has the potential for the most favorable efficiency and time savings [10,11]. If existing criteria are no longer satisfied, prefabricated elements or systems can be removed individually for expansion and reused to produce new buildings, providing the opportunity for adaptability.

Even though the materials utilized in modular buildings are generally identical to those employed in on-site installations, they exhibit enhanced quality since the components are fabricated within regulated conditions [12]. Timber constructions possess a notable competitive edge in this aspect due to their substantial degree of prefabrication (quick and precise assembly), lightweight nature [13,14], and simplicity of connections [15]. Furthermore, timber structures "*can be renewed, manipulated, and laminated*" [1]. These are favorable conditions for the effective recycling and repurposing of complete architectural elements, specific sections of buildings, and individual components [16], reducing expenses and shortening installation schedules [17]. In addition, the waste produced can be reused in the manufacturing process for various applications, which ensures a significantly cleaner and more regulated environment. Simultaneously, it enhances health and safety because the operational process is greatly minimized [15]. Given all these benefits, timber may be considered an optimal modularization material. Therefore, the utilization of timber as an off-site material has been extensively researched and promoted in the industry.

Recently, there has been a comprehensive evaluation of prefabricated/modular structures, examining various aspects related to management strategies [18–20], structural systems in high-rise buildings [7], building design [8], environmental and economic performance [21], as well as the features of modular construction utilizing exclusively cross-laminated timber [22]. However, the specific advancements and recent innovations in prefabricated/modular timber structures, which include light-frame, mass timber, and prefabricated hybrid elements, systems, or structures have not been reviewed and critically analyzed to identify current trends and challenges in the field.

Therefore, the objective of this research entails the assessment of the current state of the art regarding modular timber construction, analyzing its evolution as a research field and critically assessing the current trends and challenges. This contribution aims to assist researchers in understanding the current state of technology and orient them towards researching the most impactful needs. To achieve this, the applied methodology included the following: (i) to quantitatively evaluate the existing literature; (ii) to develop a scientific mapping analysis utilizing a co-word network approach; (iii) to establish the evolution of the underlying themes within this domain; (iv) to identify future trends and gaps in the current literature; and (v) to provide valuable insights and directions for future research endeavors. The organization of the article encloses a comprehensive methodology section (Section 2), a scientometric analysis and presentation of the results (Section 3), a critical analysis of the results (Section 4), and a conclusion section (Section 5), which encapsulates the essential findings and potential approaches to further investigation.

2. Methodology

2.1. Bibliographic Search

The initial phase involved acquiring data and selecting the primary source of the Web of Science (WOS) collection database. This database was chosen due to its reputation for including many valuable publications, such as journals, book chapters, conference proceedings, and other scholarly works [23]. A comprehensive set of keywords was developed by drawing upon the relevant literature and diverse reviews [7,18,24,25]. These keywords were then categorized into two themes delineated in Table 1: (a) prefabricated construction/modular construction and (b) wood. In the case of the former, terms associated with prefabrication and modularization were also considered to ensure the inclusion of all pertinent information. WOS includes multiple search criteria, and the following were taken into consideration: (a) the topic, which encompasses various parameters such as the title, abstract, author keywords, and Keywords Plus (additional keywords automatically generated by the WOS website concerning the research topic); (b) the abstract, which provides a summary of the existing knowledge about the subject matter under investigation; and (c) the title, which encapsulates keywords that reflect the main issues addressed in the study [26]. As for the relationship between the keywords, the *"OR"* connector was utilized for the terms prefabricated construction/modular construction and their associated terms, while the "*AND*" connector was employed to incorporate the term wood. Therefore, the selected literature must contain at least one keyword from each theme.

Table 1. Selected keywords, connectors, and associated terms applied to the search criteria.

Theme 1	Connector	Theme 2
Topic: prefab* pre-fab* modular* *assembl*		
OR	*AND*	Title: timber* OR wood*
Abstract: "offsite construction" "off-site construction" "offsite manufacture" "off-site manufacture" "modular building" "modular construction" "modular technology" "prefab building" "prefab construction" "pre-fab building" "pre-fab construction" "industrialized construction" "industrialized building" "panelized construction" "tilt-up construction" "volumetric construction" "prefinished construction" "preassembly building" "preassembly construction" "plug & play modular"		

By defining the search domain based on the parameters above (topic, abstract, and title), a total of 3573 publications were retrieved. However, the search was restricted to journal articles, as these documents are considered high-quality research studies [21]. Moreover, the search was limited to specific fields, namely, civil engineering, construction building technology, architecture, green sustainable science technology, engineering manufacturing, management, and industrial engineering. The selected information was limited to publications written in English. Finally, the analysis period was set from 1990 to November/2023 to elucidate the development and evolution of prefabrication with wood and its connection to future trends, obtaining 623 articles. Subsequently, these articles underwent analysis, resulting in the exclusion of papers focusing on timber shells, timber grid shells, folded structures, wooden domes, or timber textile modules, as these elements or structures did not align with the definition of prefabrication levels (linear, panelized systems, or volumetric) [4,15]. Furthermore, the study did not embrace research on elements or structures based on other materials, even if it included relevant parts fabricated from wood or cellulose-based materials, plastic, or biocarbon, which are increasingly attracting attention for their utilization in the sustainable advancement of functional materials [27,28].

It is important to emphasize that the compiled publications must examine several aspects of the performance of prefabricated/modular timber elements or structures. These aspects included the structural, acoustic, hygrothermal, and thermal characteristics. Furthermore, the scope of the analysis covered single-level and multi-level constructions made of light-frame and mass timber, including cross-laminated timber (CLT), nail-laminated timber (NLT), dowel-laminated timber (DLT), glue-laminated timber (GLT), and laminated veneer lumber (LVL). The investigation also explored hybrid elements combining mass timber with steel or concrete. In addition to these technical aspects, the review focused on the design, construction, production, management, and life cycle assessment (LCA) of prefabricated and modular timber structures. Finally, a comprehensive final assessment was carried out based on a thorough examination, leading to the identification of 11 papers that lacked the author's keywords, which were vital to developing the scientometric analysis. Therefore, after the selection criteria, a total of 409 articles were considered.

2.2. Scientometric Analysis

The subsequent step involved executing a scientific mapping analysis based on a co-word network using Scientific Mapping Analysis Software Tool (SciMAT), software developed by the University of Granada (Spain) in 2011. According to [29], this tool incorporates a range of essential functionalities such as data retrieval, data preparation, network extraction, network normalization, mapping, analysis, and visualization. In this investigation, the organization of co-word analysis facilitated an in-depth exploration of the conceptual framework of the topic through the associations between keywords. This powerful technique allowed for obtaining insights into the principal investigation concepts while also enabling distinguishing the trajectory of their evolution and the interaction between scientific research themes [30]. These research themes represent different research fields and can be visualized on the two-dimensional strategic diagram in Figure 1.

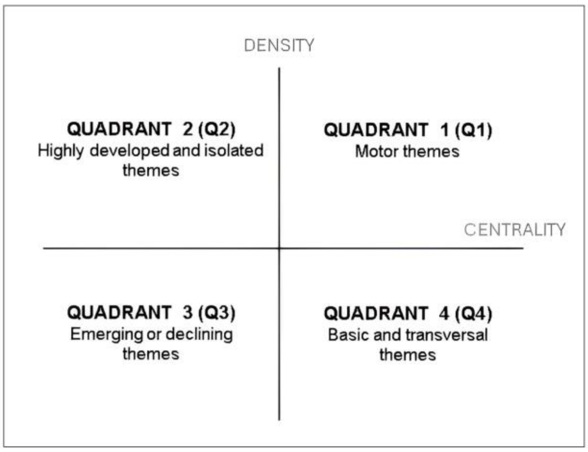


Figure 1. Strategic diagram adapted from [31].

3. Results

This section presents an interpretation and examination of the outcomes originating from the co-word network of the scientific mapping analysis. This outline is structured into two distinct subsections: (i) a comprehensive thematic analysis conducted by periods with the relationship between the diverse themes, and (ii) an assessment of the thematic conceptual evolution.

3.1. Thematic Analysis Conducted by Periods

As stated before, the investigation involved the analysis of articles published between 1990 and 2023. The research was divided into three subperiods: (i) 1990–2004, (ii) 2005–2019, and (iii) 2020–2023 (see Table 2). Particular attention was given to CLT's emergence and subsequent development as an industrial product, which commenced in 2005 [32]. Furthermore, to conclude the same subperiod, constructing the tallest all-timber Mjøstårnet building in 2019, located in Norway, marked another crucial milestone. It is important to note that, as defined by the Council on Tall Buildings and Urban Habitat (CTBUH), an all-timber building is characterized by having its main vertical and lateral structural elements, as well as its floor spanning systems, constructed primarily from timber while other materials, such as concrete elements, play a secondary role in the structure [33]. The three subperiods provide a comprehensive understanding of the topic and illustrate the progression of various factors such as the number of documents, number of citations, h-index, and average citations attained.

Table 2. Subperiods from 1990 to 2023 and the number of publications developed during the subperiods.

Subperiod Name	Number of Documents
1990–2004	11
2005–2019	198
2020–2023	200

3.1.1. Subperiod 1990–2004

1. Quantitative measures and strategic diagram.

The 11 documents of this period (about 2.7% of all published papers) were linked with specific themes; thus, it can be observed that this subperiod exhibits a relatively low number of keywords associated with each document. Following the strategic diagram illustrating the characteristics of this initial period (see Figure 2), it becomes evident that there are no motor themes (1st quadrant) or highly developed themes (2nd quadrant). Additionally, there is an absence of emerging or declining themes (3rd quadrant) and basic themes (4th quadrant) that guide the field of prefabricated timber construction. However, this period is focused on two distinct clusters. The first cluster, denoted as TIMBER-STRUCTURES (within the 1st and 2nd quadrants of the strategic diagram), can be considered the motor topic of the research. The second cluster, DESIGN, appears to possess characteristics of a motor or basic theme (within the 1st and 4th quadrants of the strategic diagram). Upon closer examination of the quantitative measures presented in Table 3, the first theme has the highest number of citations, amounting to 38, while the second theme has 27 related publications. As previously mentioned, due to the limited number of papers associated with this specific period's themes, both exhibit relatively low h-index scores, further emphasizing the scarcity of scholarly contributions in this domain.

Table 3. Performance measures for the themes of the subperiod 1990–2004.

Theme Name	Number of Documents	Number of Citations	Average of Citations	h-Index
TIMBER-STRUCTURES	3	38	12.66	3
DESIGN	3	27	9	3

2. Thematic network

- Themes
  The network graph analysis reveals that the clusters of TIMBER-STRUCTURES and DESIGN (Figure 3) are highly interconnected (in other words, each cluster focuses on a specific topic, and all their keywords are related between them). The first cluster is related to various aspects and components involved in constructing and evaluating timber structures, including *steel, fiber-plaster-boards, trusses, walls, experimental-test, fem-analysis, structural-performance*, and *joints*. On the other hand, the second cluster, centered around the efficient performance of structures and design processes, delves into concepts such as *resistance, reliability, construction, civil-engineering, behavior, loads*, and *connections*.

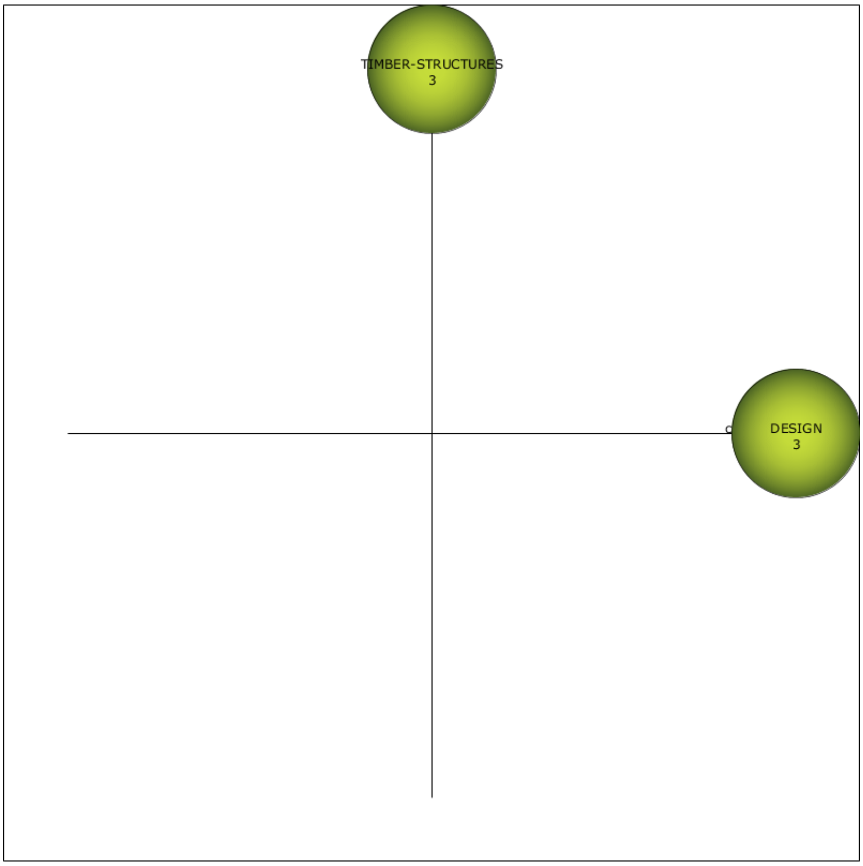


Figure 2. Strategic diagram for the 1st subperiod with two distinct clusters (1990–2004).

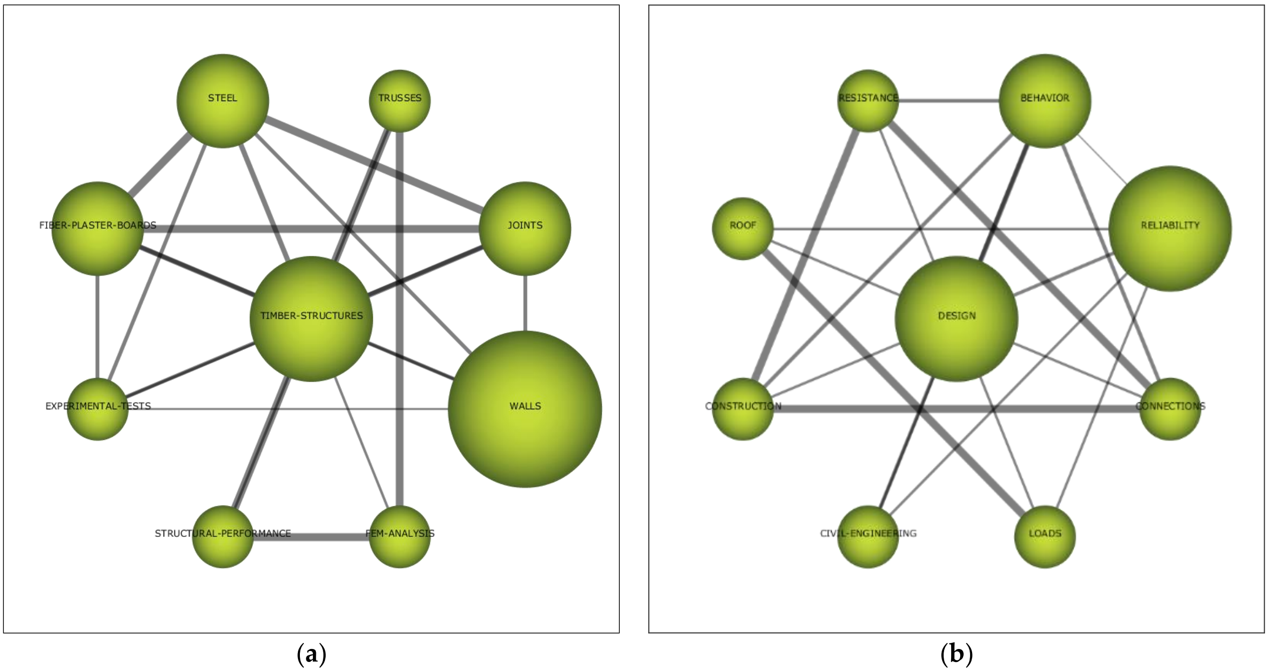


Figure 3. Cluster networks of the 1st period: (**a**) TIMBER-STRUCTURES; (**b**) DESIGN.

- Relationship between themes with most-cited articles
  The collection of keywords provides valuable insights into the research focus during this period. For example, Dobrila and Premrov [34] discussed the im-

portance of the composite timber frame–fiberboard panel wall design. Their study demonstrated that inserting diagonal steel strips attached to the wooden structure represents the most effective method to enhance the resistance and flexibility of the elements. Among the investigations that concentrate on finite element method (FEM) analysis in timber structures, the work of [35] stood out due to its introduction of an analytical technique for examining the behavior of light-frame wood structures when subjected to static loads. The study primarily focused on the behavior of substructures and system components that have not been previously included in a comprehensive structural model. The findings indicate remarkable similarities between the experimental and analytical outcomes. Similarly, Tarabiate and Itani [36] described a three-dimensional computer model for evaluating light-frame wood constructions. Their study showcased the model's capability to explore various structural configurations and generate design requirements for wood structures.

3.1.2. Subperiod 2005–2019

1. Quantitative measures and strategic diagram.

One hundred and ninety-eight (198) documents were published within the research focused on prefabricated timber construction in the specified subperiod, representing a significant increase compared to the initial period. The comprehensive analysis of these publications revealed the presence of nine distinct research themes, which are subsequently described through the quantitative measurements presented in Table 4 and strategic diagrams illustrated in Figure 4. Within the 1st quadrant of the strategic diagram, the theme CONNECTIONS emerged as a highly relevant and influential area of study (motor theme). This theme achieved an impressive number of citations, amounting to 2028, making it the most frequently referenced theme. Furthermore, it had the highest number of published articles, with a total of 76, thus solidifying its substantial impact on the research field, as evidenced by its high h-index score of 26. Another motor theme within this subperiod is LIFE-CYCLE, which, despite being ranked fourth in the number of citations (517), exhibited a low number of published articles related to the topic (13). For this reason, it presented a relatively low impact within the research field, as indicated by its h-index score of 11.

Table 4. Performance measures for the themes of the subperiod 2005–2019.

Theme Name	Number of Documents	Number of Citations	Average of Citations	h-Index
CONNECTIONS	76	2028	26.684	26
MODELING	26	521	20.038	14
WALLS	24	454	18.917	13
INDUSTRIALIZED-CONSTRUCTION	21	723	34.429	14
NUMERICAL-MODELING	16	215	13.438	10
HYGROTHERMAL-PERFORMANCE	14	339	24.214	11
LIFE-CYCLE	13	517	39.769	11
THERMAL-PERFORMANCE	11	225	20.455	9
CONCRETE	10	353	35.3	8

In the second quadrant of the strategic diagram, there are highly developed and isolated themes, HYGROTHERMAL-PERFORMANCE, MODELING, and THERMAL-PERFORMANCE. HYGROTHERMAL-PERFORMANCE ranks in the seventh position regarding the number of citations (339). Similarly, MODELING and THERMAL-PERFORMA NCE rank in the eighth and ninth positions, respectively, with 225 and 215 citations. The theme WALL, situated within the 3rd quadrant of the strategic diagram, can be perceived as either an emerging or declining theme despite occupying the fifth position regarding the number of citations, with a count of 454. It does not make a substantial impact, as evidenced by its relatively low h-index score of 13. Finally, in the 4th quadrant, one notes themes deemed relevant to the research field (basic and transversal themes). INDUSTRIALIZED-CONSTRUCTION emerges as the central and most basic theme, with 723 citations. The next theme is MODELING, with 521 citations, while CONCRETE ranks sixth in the number of citations, with a count of 353. It is crucial to emphasize that the themes positioned within the last three quadrants (2nd, 3rd, and 4th) exhibit the lowest impact or h-index scores, predominantly due to the limited number of published papers dedicated to the themes.

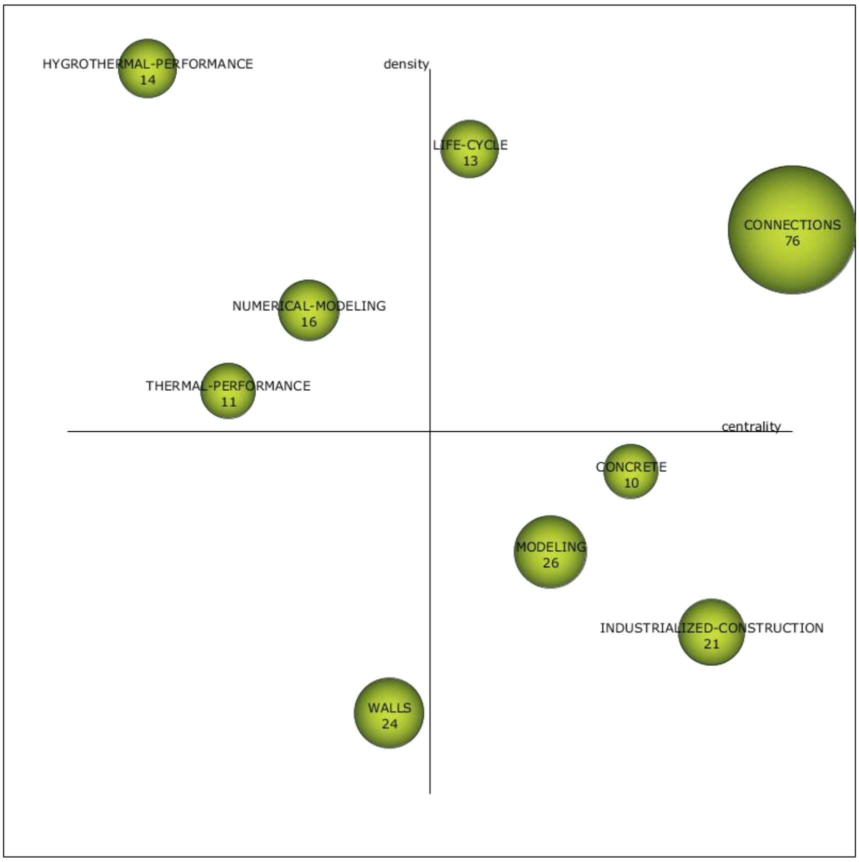
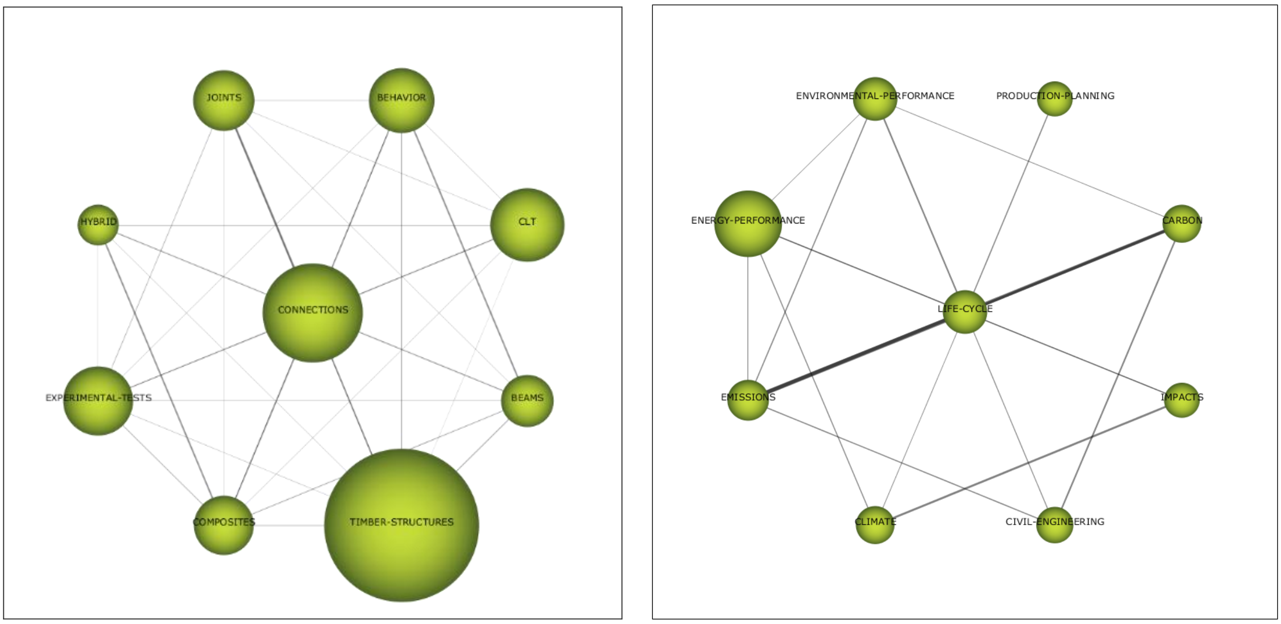


Figure 4. Strategic diagram for the 2nd subperiod (2005–2019).

2. Thematic network
   - Motor themes

     Analyzing the network graph (Figure 5a), it can be observed that the principal motor theme, CONNECTIONS, forms a highly interconnected cluster that explores various structure-related aspects. These aspects include *timber-structures*, *behavior*, *experimental-tests*, and structural elements such as *beams*. It is also linked to engineered timber materials like *clt* and the combination of timber with other materials, such as *hybrid* and *composites*. It is worth noting that during this period, certain studies assessed the performance of connectors in prefabricated timber-framed walls [37] or prefabricated timber composite systems [38].

     Moving on to the second motor theme, LYFE-CYCLE (Figure 5b), this cluster covers many aspects related to the Life Cycle Assessment (LCA) methodology, such as *energy-performance*, *environmental-impact*, *emissions*, *carbon*, *impacts*, and *climate*. Additionally, it includes other terms associated with construction processes, such as *civil-engineering* and *production-planning*. However, it is essential to note that despite being a motor theme, it does not have an extensive collection of published articles. This can be attributed to the lack of specific rules governing the LCA of whole buildings and wooden building products before 2011. Consequently, this led to a vast dissimilarity in approaches, results, and interpretations among various studies, as highlighted by [39]. For instance, the study conducted by [40] emphasizes prefabricated techniques, specifically wood-frame systems, as an alternative approach to reducing a building's carbon footprint.



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

Figure 5. Cluster networks of the motor themes: (**a**) CONNECTIONS; (**b**) LYFE-CYCLE.

- Highly developed and isolated themes
  In the second quadrant, the theme NUMERICAL-MODELING (Figure 6a) delves into various aspects related to the seismic behavior of structures. These aspects include *analysis*, *seismic-performance*, *cyclic-testing*, materials, and structural elements such as *steel*, *timber-framed-walls*, and *timber-shear-walls*. Furthermore, this theme considers components in the design of facades, such as *openings* and *sheating*. The research undertaken by [41] investigated a hybrid structural system comprising a steel moment-resisting frame and prefabricated infill light-frame timber shearwalls. The author stated that quasi-static cyclic and monotonic loading tests were carried out to analyze such structures' seismic performance accurately, and the results were evaluated using a numerical model.
  HYGROTHERMAL-PERFORMANCE (Figure 6b) focuses on factors leading to potential issues, such as *mold* and *moisture*. It covers the parameter measurement of insulation performance such as *u-values*, evaluation forms such as *simulations*, construction elements such as *assemblies*, and construction elements such as *highly-insulated-wood-frame-walls*. Also, it is related to other factors that impact hygrothermal performance, such as *air-leakage* and *risks*. Moving forward, THERMAL-PERFORMANCE (Figure 6c) is linked to energy transfer aspects, such as *heat*, materials, and construction typologies, such as *insulation*, *phase-change-materials*, *systems*, *prefabricated*, and *residential-buildings*, and processes such as *retrofitting*. Additionally, it includes other keywords, such as *interviews*. As the demand for energy-efficient buildings continues to rise, an urgent need is to improve building envelope insulation [42]. Glass et al. [43] focused on analyzing the moisture characteristics of highly insulated wood-frame walls in mixed-humid climates. The authors of [44] employed hygrothermal simulations and field measurements to analyze the moisture content in the surface layers of cross-laminated timber (CLT) panels. Other studies have attempted to opti-

mize the structural and thermal performance of light wood-frame structures to enhance thermal efficiency and structural capacity [45].

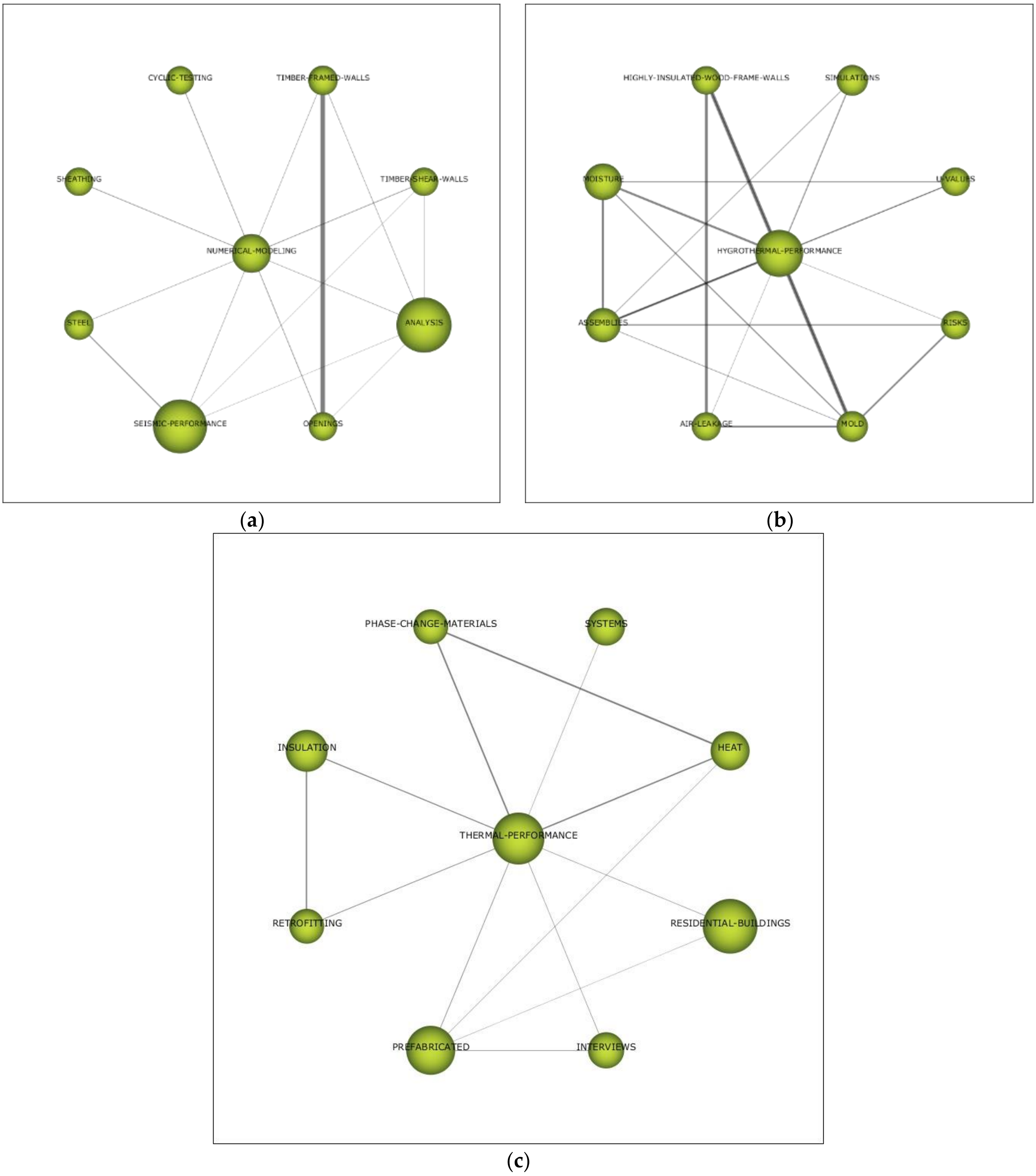


Figure 6. Cluster networks of the highly developed and isolated themes: (**a**) NUMERICAL-MODELING; (**b**) HYGROTHERMAL-PERFORMANCEM; (**c**) THERMAL-PERFORMANCE.

- Emerging or declining themes
  The theme WALLS (Figure 7) focused on structural forces, characteristics that influence the behavior of structures, and methodologies employed to measure them, such as *loads*, *ductility*, *failures*, *full-scale-tests*, and *nonlinear*. It also includes architectural typologies and structural elements, such *as buildings*, *frames*, and

timber-framed-structures. For instance, Van De Lindt et al. [46] focused on examining the damage incurred by lateral load-carrying assemblies within wood frame structures, specifically shearwalls. The researchers also explored the potential for developing a holistic predictive damage model for the entire structure and integrating it into seismic design practices.

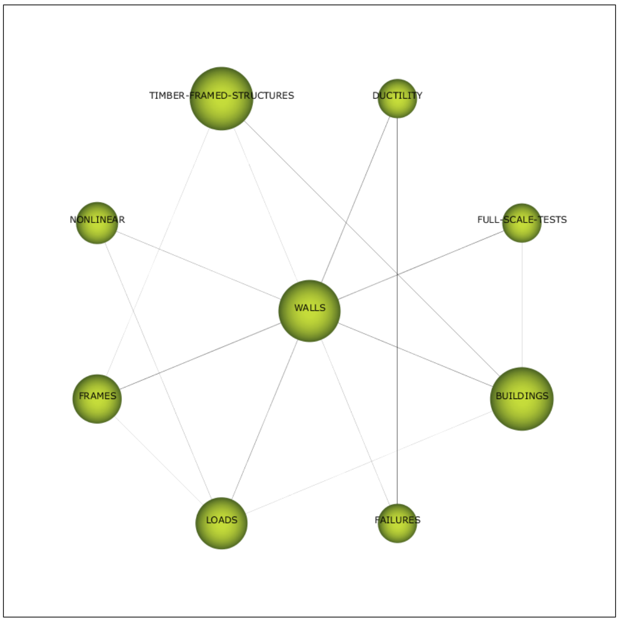


Figure 7. Cluster networks of the emerging or declining themes: WALLS.

- Basic and transversal themes
  Among the themes that hold significant relevance to the field but have not yet been extensively explored, we found the theme MODELING (Figure 8a), which was linked to various aspects of timber structures, encompassing *structural-performance, design, strength*, and *fire-behavior*; different types of timber structures, like *light-frame-structures*; and structural support elements, such as *shear-walls*. It was also associated with hurricanes and wind. The authors of [47] presented a three-dimensional model of a two-story house design utilizing a prefabricated timber-frame structural system. Using parametric analysis, the study offered a single-variable parameter to find the suitable glazing area size value for all modern prefabricated timber buildings.
  INDUSTRIALIZED-CONSTRUCTION (Figure 8b) is a highly interconnected cluster that incorporates various topics related to the construction process and structural design, such as *modular-construction*, *timber-construction*, *innovation*, *shrinkage*, and *performances*, as well as the structural components of buildings, such as *floors* and *concrete-composite-structures*. Novel modular structures that could facilitate the rapid fabrication of new residential complexes were proposed in this period. As demonstrated by [48], a versatile construction system in which the prominent structural members, made by combining steel–timber hybrid shearwall and floor components, present a low environmental impact, given their recyclability and quick replaceability. Similarly, Ref. [49] proposed an innovative composite steel–timber prefabricated floor component that showcased the system's potential in bearing capacity, stiffness, and construction methods.
  Finally, the theme CONCRETE (Figure 8c) primarily focuses on exploring structural timber elements, such as *mass-timber* and *timber-concrete-composite-structures*. Furthermore, it mainly delves into materials that bond these elements, including *adhesives* and *gluing*. It also covers structural topics like *shear*, *balances*, and *reinforcement*, and numerical methods like *fem-analysis*. To illustrate this point, some

researchers have dedicated their efforts to conducting experimental tests that examine the structural performance of prefabricated timber–concrete composite floors [50,51].

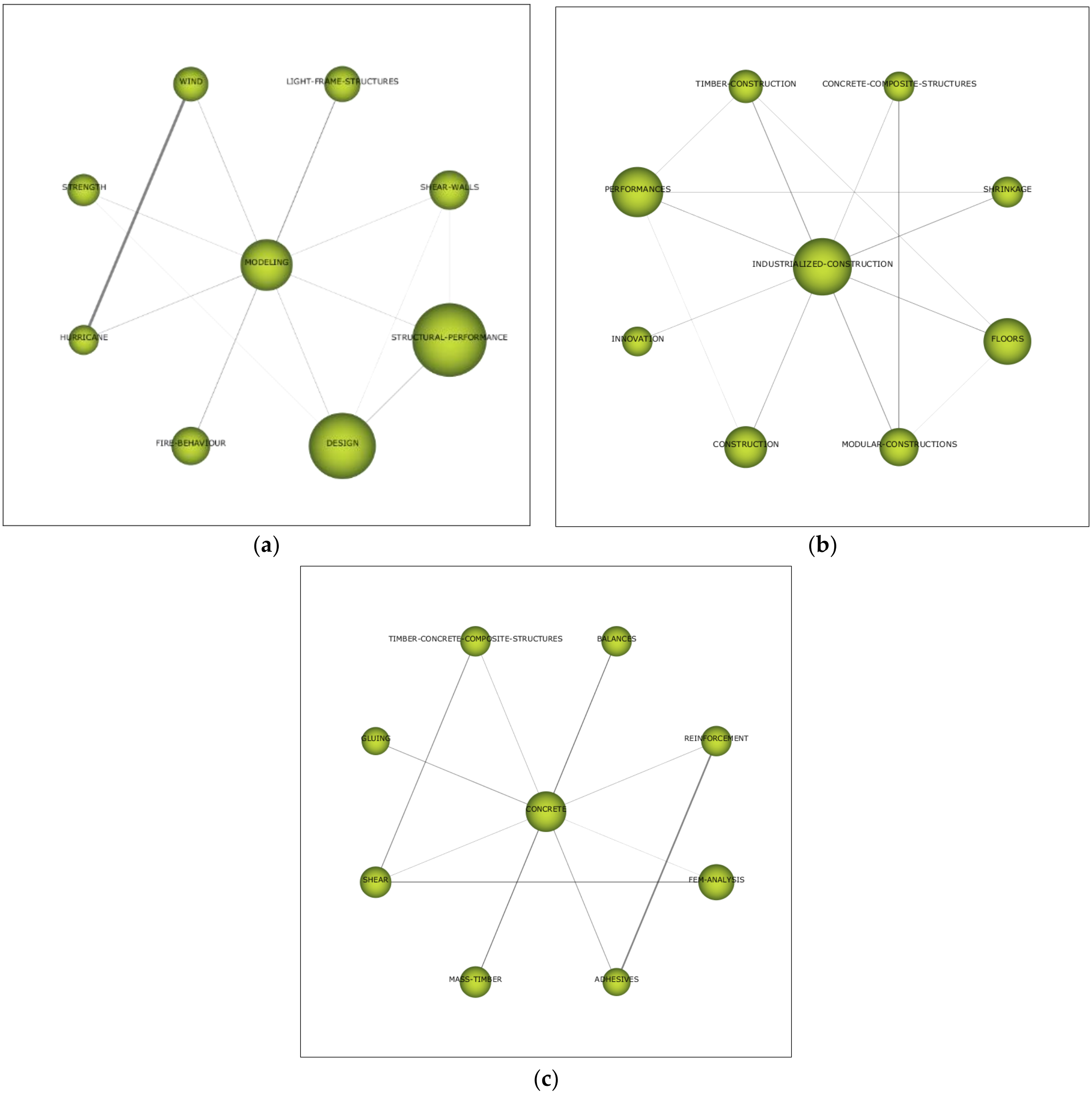


Figure 8. Cluster networks of the of the basic and transversal themes: (**a**) MODELING; (**b**) INDUSTRIALIZED-CONSTRUCTION; (**c**) CONCRETE.

- Relationship between motor and basic themes with most cited articles
  In this period, numerous investigations persisted to determine the structural behavior of light-framed prefabricated timber buildings [52–55]. Nonetheless, the comprehensive examination of the structural performance of mass timber construction methods has not been fully addressed. Among the most crucial aspects of the design process in mass timber structures lies the design of connections, as they impact the joining of members and the load capacity, stiffness, and ductility of the entire system [56].
  Regarding the most frequently mentioned subjects (related to the motor or fundamental themes and their networks), a noteworthy instance of connections and

their strong relationship with CLT was the complete-scale seven-story framework composed of CLT panels following the European seismic standard Eurocode 8. It was subjected to earthquake-induced loading on a three-dimensional shaking table. The seven-story structure was part of the research project "SOFIE-Sistema Costruttivo Fiemme", whose goal was to exhibit the capability to self-center, possess high stiffness, and possess sufficient flexibility to avert brittle failures. Additionally, tensile joint assemblies were developed, and their importance in dissipating energy in structures with rigid CLT panels became apparent. Lastly, the authors noted that the seven-story structure experienced relatively strong accelerations at higher levels, which could result in secondary damage and should be addressed in future investigations [57]. Another approach to the same topic was the work of [58]. The study examined alternative mechanical "dry-dry" connections previously integrated into a prefabricated concrete slab. Direct shear tests were conducted on small blocks constructed from glulam segments affixed to a prefabricated concrete slab. The experiment measured the relationships between shear force and relative slip and calculated mechanical properties, such as slip moduli and shear strengths. The findings indicated that innovative connection technologies for precast concrete slabs can perform comparably to cast-in situ slabs while being more cost-effective.

Lastly, one of the most frequently addressed topics was the energy efficiency of timber buildings. The authors of [59] utilized a consequential-based lifecycle approach to examine the carbon implications of conventional (Swedish building regulations) and low-energy (Swedish passive home standards) versions of three timber multi-story building systems. The building systems were constructed using mass timber (CLT components), beam-and-column structures (glulam and LVL components), and prefabricated modules of light-frame volume elements. The analysis encompassed the entire resource chain throughout the lifecycle of the building, tracking carbon flows from fossil energy, industrial processes, changes in carbon stocks in materials, and potential avoidance of fossil emissions through the substitution of fossil energy with woody residues. In conclusion, the study emphasized the potentially significant role of multi-story timber structures in carbon-efficient construction by demonstrating that the low-energy variant of the CLT building emits the least amount of carbon over its lifespan. In comparison, the standard beam-and-column construction exhibits the highest lifespan emission.

3.1.3. Subperiod 2020–2023

1. Quantitative measures and strategic diagram.
   CONNECTION emerged as the dominant motor theme (Figure 9). It accumulated the highest number of citations, totaling 518, and had the most significant number of published documents, reaching 80. However, it had a relatively low impact on the field of research, as indicated by its h-index score of 12. The following motor theme was ENERGY-PERFORMANCE, which ranked third in the number of citations with a count of 183. However, the number of published papers was comparatively low (36), resulting in a correspondingly low h-index score of 9. Additionally, within the first quadrant of the strategic diagram, other motor themes emerged: CIRCULAR-ECONOMY and COMPOSITES. The former had a number citation count of 127, while the latter had 123 citations. Both themes shared the same number of publications, 16, and achieved an h-index score of 7, as can be seen in Table 5.

Table 5. Performance measures for the themes of the subperiod 2020–2023.

Theme Name	Number of Documents	Number of Citations	Average of Citations	h-Index
CONNECTIONS	80	518	6.475	12
ENERGY-PERFORMANCE	36	183	5.083	9
CONSTRUCTION	32	232	7.25	8
BUILDING-ENVELOPE	19	127	6.684	8
CIRCULAR-ECONOMY	16	127	7.938	7
COMPOSITES	16	123	7.688	7
FLOORS	14	84	6	5
MODELING	13	98	7.538	5
SEISMIC-PERFORMANCE	13	74	5.692	6

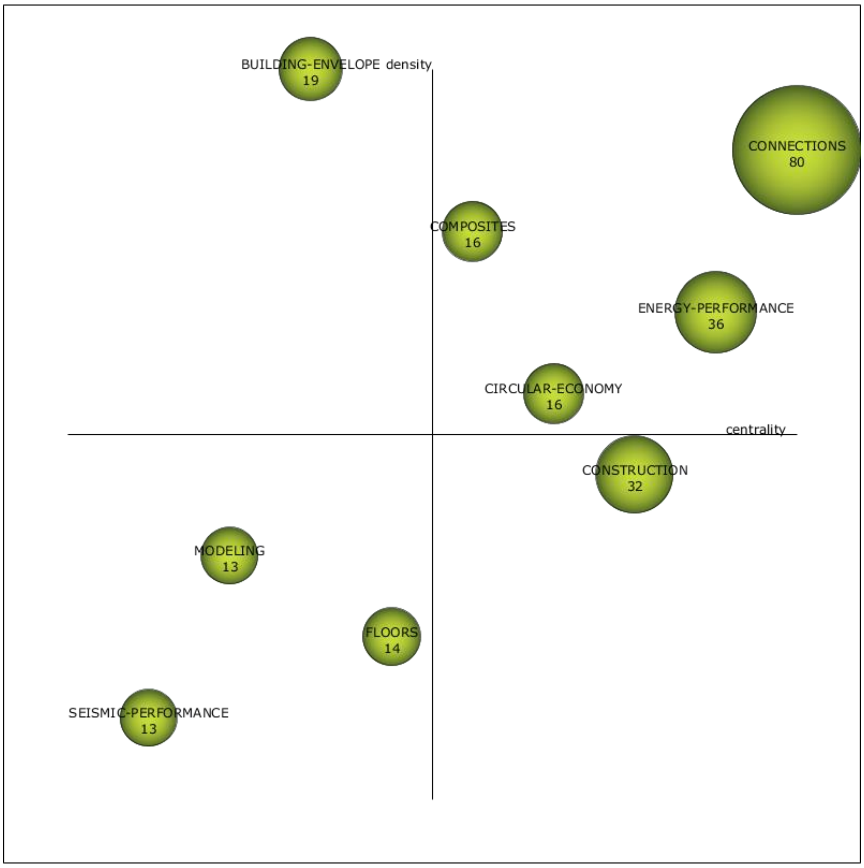


Figure 9. Strategic diagram of the 3rd subperiod (2020–2023).

Moving on to the second quadrant, the highly developed and isolated theme was BUILDING-ENVELOPE. This theme was characterized by 19 published documents, 127 citations, and an h-index score of 8. In the third quadrant, we observed emerging or disappearing themes such as FLOORS, MODELING, and SEISMIC-PERFORMANCE. FLOORS was represented by 14 published documents and achieved 84 citations. The h-index score was the lowest among all the themes analyzed, standing at 5. On the other hand, MODELING and SEISMIC-PERFORMANCE boasted citation counts of 98 and 74, respectively. The h-index score for MODELING was 5, while for SEISMIC-PERFORMANCE, it was 7. Finally, the fourth quadrant was occupied by the basic and transversal theme, CONSTRUCTION. This theme ranked second in the number of citations, with a count of 232. It was accompanied by 32 published documents and an h-index score of 8.

Upon comparing this subperiod to the previous one, the number of themes remained relatively consistent. However, there was a noticeable increase in the quantity of motor themes within the quadrant. Additionally, the number of published documents in this subperiod, totaling 200, was almost on par with the previous subperiod. Similarly, we found that the motor themes (first quadrant) and basic themes (fourth quadrant) continued to be the most highly cited and were associated with the highest number of documents. It is worth noting that the analysis only covered three years, yet it was evident that researchers have shown a growing interest in the motor and basic themes.

2. Thematic network

- Motor themes

As illustrated in the thematic networks, the motor themes CONNECTIONS (Figure 10a) and ENERGY-PERFORMANCE (Figure 10b) are closely connected clusters (each cluster is focused on a specific topic). The first motor theme is mainly focused on the conditions of structures under loading and construction materials, which include *structural-performance, experimental-tests, shear, performances, behavior, clt*, and *timber-concrete-composite-structures*. Additionally, this cluster incorporates analytical models such as *fem-analysis*. On the other hand, the second motor theme is associated with crucial measures for assessing the sustainability of a structure, including *life-cycle, environmental-performance, thermal-performance, carbon*, and *heat*. In addition, it contains structural and construction topics such as *residential-buildings, timber-structures*, and *blast*. Although CLT is now being utilized for previously considered improbable structures, the technology for connecting these elements is still evolving [60], and it is discussed in various papers published during this period [61,62]. Furthermore, there is a specific focus on enhancing the energy dissipation capacities of mass timber building assemblies by utilizing steel energy-absorbing connections [63].

Another motor theme that exhibits significant connectivity is CIRCULAR-ECONOMY (Figure 10c), which delves into construction and structural concepts, including *architecture, design-for-disassembly, business-models, systems, challenges*, and *buildings*. It also covers construction materials such as *mass-timber* and *concrete*. The circular economy concept is extensively discussed in the publication by [64], which presents a systematic literature review highlighting significant knowledge gaps and urgent research needs for developing holistic approaches to circularity potentials for panelized mass timber structures.

In contrast to the previous ones, the theme COMPOSITES (Figure 10d) does not possess a well-connected cluster. This theme focuses on the structural behavior of the structures, construction elements, and materials such as *loads, collapse, strength, resistance, part-I, validation, beams*, and *steel*. In the scope of composites, several investigations concentrate on the structural behavior of prefabricated timber-concrete composite elements with innovative connections [65,66].

- Highly developed and isolated themes
  The theme BUILDING-ENVELOPE (Figure 11) is related to the external behavior and properties of the building's envelope. This covers various aspects, such as *hydrothermal-performance* and *airtightness.* Moreover, it covers construction elements, potential issues, and the materials utilized in the building envelope, such as *wood-frame-walls, walls, mold, moisture, air-barrier*, and *oriented-strandboard*. Research efforts have been ongoing to study timber-framed and mass-timber external wall assemblies, as timber proves to be effective in reducing thermal bridges due to its low thermal conductivity, which enhances a building envelope's overall energy efficiency [67]. For instance, [68] demonstrated the correlation between the hygrothermal simulation tool (WUFI) model output and the measured values of OSB moisture content (MC), cavity temperature (T), and cavity relative humidity (RH) for wood-framed walls with various exterior insulations in cold climates.

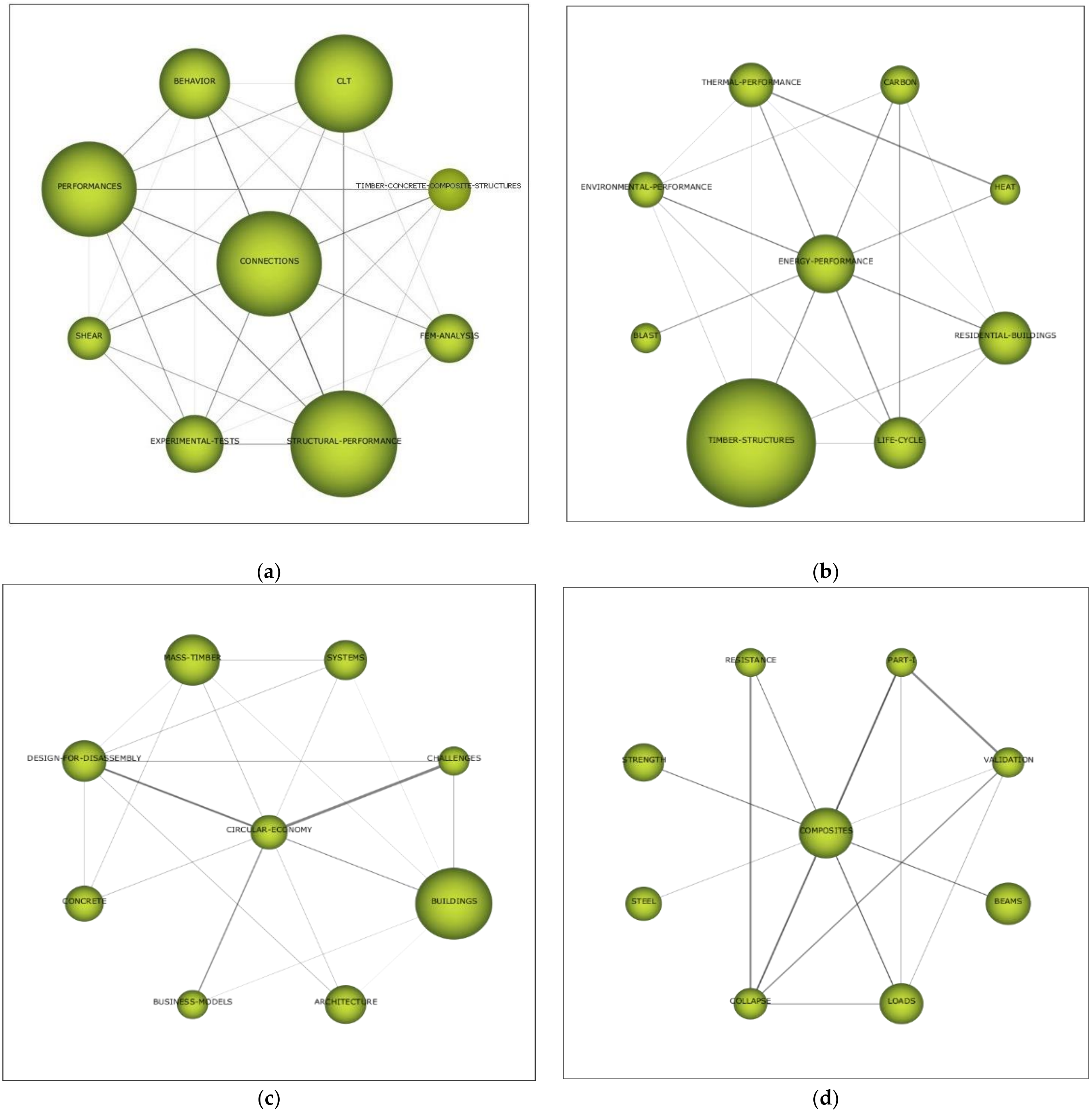


Figure 10. Cluster networks of the basic and transversal themes: (**a**) CONNECTIONS; (**b**) ENERGY-PERFORMANCE; (**c**) CIRCULAR-ECONOMY; (**d**) COMPOSITES.

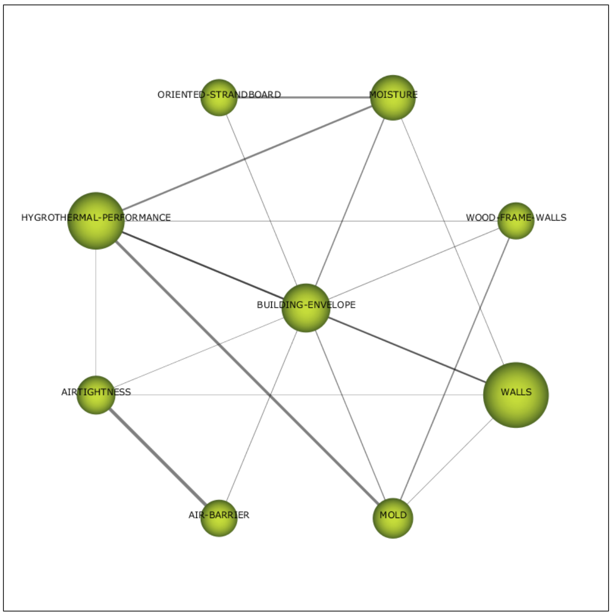


Figure 11. Cluster networks of the of the basic and transversal themes: BUILDING-ENVELOPE.

- Emerging or declining themes
  FLOORS (Figure 12a) covers structural material properties and processes to improve the structural material properties such as *flexural-behavior* and *prestress*, and types of connections including *shear-connections, joints*, and *screws.* It also covers the parts and features of the structures, including *elements* and *prefabricated*. The analysis presented by [69] shed light on the acoustic performance of timber buildings and complex composite floor systems in the Australian construction industry. The study indicated that prefabricated construction methods showcased improved performance compared to on-site construction. However, direct comparisons are challenging due to the varying timber products and construction techniques. Thus, establishing well-defined measurement methods, predictive models for sound insulation properties, and numerical simulations for airborne and impact sound transmission becomes imperative.
  The theme MODELING (Figure 12b) focuses on the structural behavior of systems, structural elements, and the evaluation of processes. This includes *fragility, failures, post-tensioned*, *stiffened-engineered-timber-wall-systems*, *timber-framed-structures*, and *damage-assessment.* In addition, it covers technology types and visual media such as *digital-design* and *virtual-design*. For example, Wei et al. [70] proposed implementing a Digital Twin model, a collection of technologies to establish seamless physical and virtual connections. This model was designed to enhance the productivity of a wood-panel construction company. The company could foresee significant waste reduction and improve overall efficiency by utilizing this model. Additionally, it facilitates the widespread application of technology by providing a holistic framework.
  SEISMIC-PERFORMANCE (Figure 12c) is related to the seismic characteristics and evaluations of the behavior of a structure, covering various factors such as *ductility, lateral-performance, damage-free*, and *analysis*. Also, it includes types of connections, *dowel*, and construction systems, such as *frames*. In the study conducted by [71], the focus was on the redesign of a nine-story residential building constructed with reinforced concrete (RC) using a hybrid disassembly building approach involving cross-laminated timber floors, glue-laminated timber frames, and concentrically braced steel frames. This research shed light on the fact that although the lateral load capacity of the hybrid building is lower than that of

the RC building, its deformation capacity is significantly higher. Moreover, the LCA results indicated that the carbon emissions from the RC building were twice as much as those emitted by the hybrid building. Therefore, material selection and construction technologies are critical for implementing circular projects in seismically active areas.

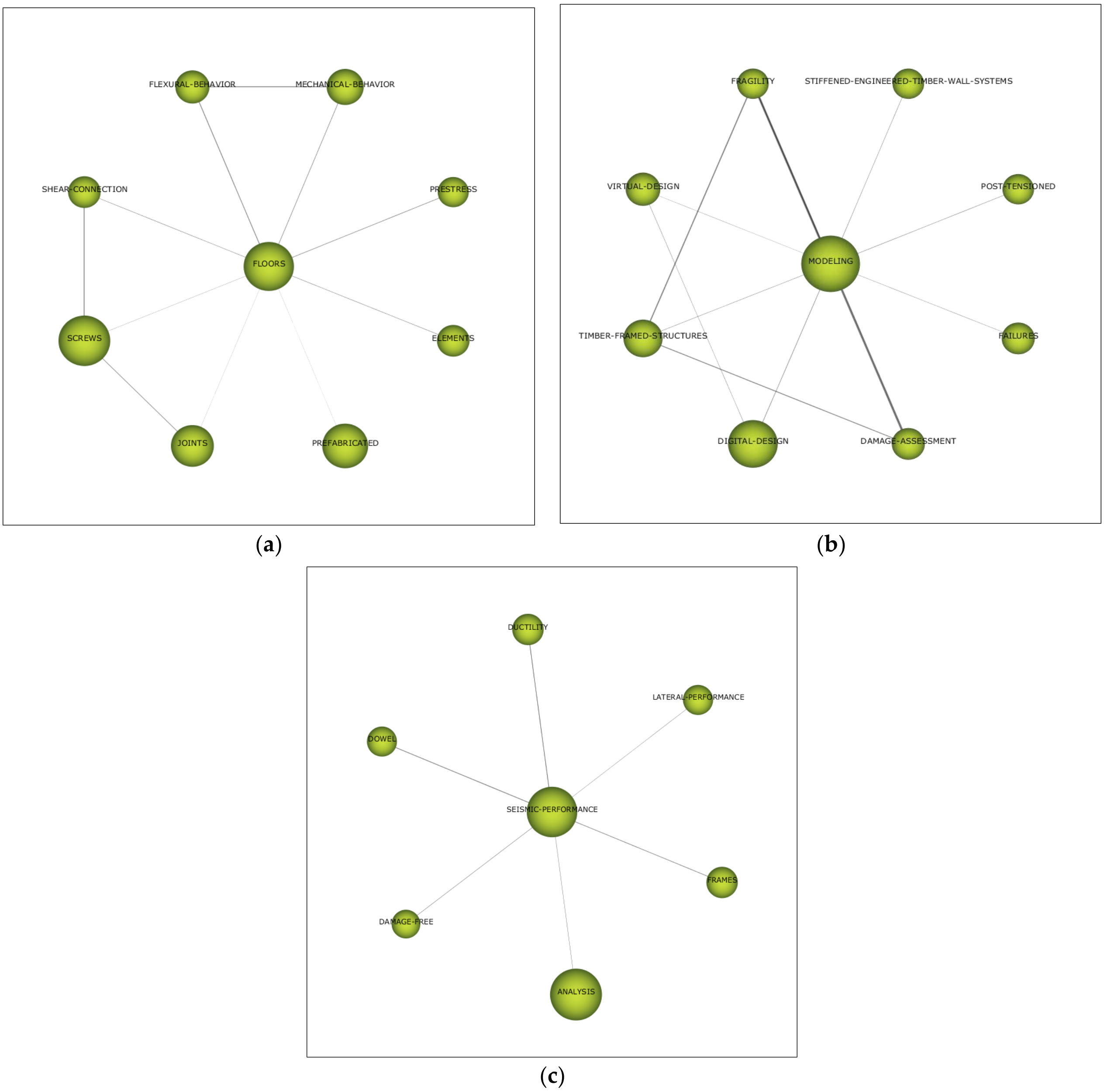


Figure 12. Cluster networks of the emerging or declining themes: (**a**) FLOORS; (**b**) MODELING; (**c**) SEISMIC-PERFORMANCE.

- Basic and transversal themes
  CONSTRUCTION (Figure 13), a relevant theme in the field, presents a highly interconnected cluster. It mainly focuses on structural processes, including *design, management, manufacturing, climate, opportunities*, and *production-planning*. It also covers the application of technology to improve them, such as *automation* and *industrialized-construction*. Understanding the multitude of variables that influence the adoption of prefabricated timber construction enhances the

implementation of the construction industrialization process. In their study, Du et al. [72] examined modern timber structures (MTSs) in China from the stakeholders' perspective. This analysis encompassed critical elements, including government policy, public awareness and acceptability, cost considerations, and the connections between designers, prefabricated component producers, and construction companies. Finally, the research provided recommendations to enhance existing perceptions, bridge the knowledge gap, and accelerate current development efforts to expand the prefabricated timber construction or MTS building sector.

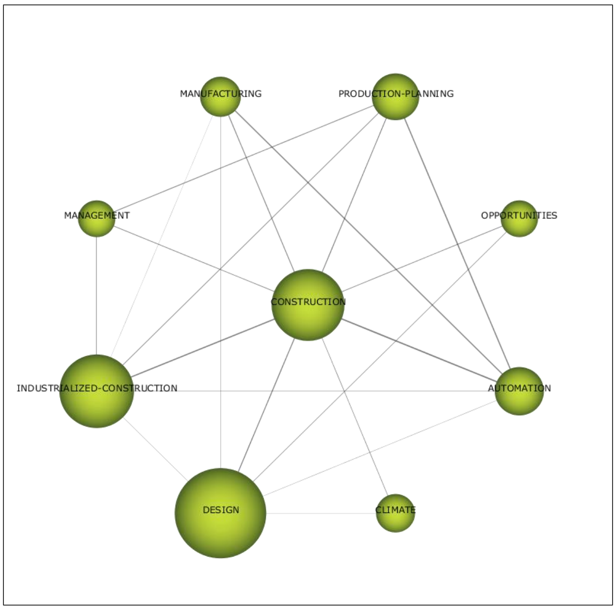


Figure 13. Cluster networks of basic and transversal themes: CONSTRUCTION.

- Relationship between motor and basic themes with most cited articles
  As shown below, the motor and basic themes' networks are the predominant subjects of reference in the publications developed in this subperiod. It is highlighted that there is a growing interest in automation in timber manufacturing with advancements in digital fabrication technology (e.g., robotic timber manufacturing). This interest stems from the potential for the fully automated production of non-standard timber structures [73] and prefabricated timber buildings. A pioneering approach to robotic manufacturing within the construction industry was introduced by developing, designing, and testing a large-scale, portable, and adaptable automated wood construction platform called TIM [74]. This mechanical system can be swiftly incorporated into existing manufacturing setups in standard carpentry projects, thereby facilitating the exploitation of synergies between traditional craftsmanship and specialized automation technology. As a result, the quality and productivity of the trade can be significantly enhanced. Additionally, the study underscored an interdisciplinary co-design approach that emphasizes cyber-physical design and production methods for multi-story timber buildings. The researchers emphasized the need to address several significant challenges in future studies before the widespread adoption of robotic timber-building platforms can be realized in the industry.
  Considering the current focus on energy performance and the circular economy, Margani et al. [75] proposed an innovative solution for rehabilitating reinforced concrete (RC)-framed buildings considering energy, seismic, and architectural factors. This solution involves the utilization of prefabricated cross-laminated timber (CLT) panels in conjunction with wood-framed panels on the exterior

walls. The combination of these panels incorporates insulation and cladding materials, enhancing the energy performance and aesthetics of the renovated building. Furthermore, innovative seismic energy dissipation devices connect the CLT panels to the existing RC frame, reducing structural damage and repair costs during seismic events. In conclusion, retrofitting significantly enhances the energy performance of multi-story residential buildings in Italy, resulting in a reduction of up to 60% in global energy demand.

Projections indicate that global demand for mass timber will continue rising upward, particularly in Australia, Japan, and New Zealand [76]. Responding to this trend, Li et al. [77] studied the out-of-plane bending behavior of Radiata Pine XLam CLT panels subjected to four-point loading. The experiments revealed brittle failure modes when the samples were loaded along the central and minor axes. Various analytical approaches were employed to evaluate the bending characteristics of the test materials, with the shear analogy proving to be the most accurate predictor. Other theoretical techniques yielded satisfactory results in determining effective bending stiffness and bending and shear strengths. The bending characteristics of CLT were further assessed through finite element analysis, with the thickness of the panels being quantitatively evaluated concerning their influence on bending behavior. The authors concluded that further parametric analysis was required to comprehensively understand these effects and providing data support for future practical applications.

3.2. Thematic Conceptual Evolution

The evolution map (Figure 14) showcases the changes in themes over time within each subperiod. According to [31], each column in the map represents the themes established during a specific subperiod. Additionally, themes from successive subperiods are connected if they share common keywords. Solid lines indicate that the connected themes have the same name or that one theme's name is part of the other theme, while a dotted line signifies that the themes share different keywords that are not their names [29].

When examining the evolution of the number of themes, we can observe a significant increase during the first and second subperiods, with four times as many themes as in the first subperiod. However, for the last subperiod, the number of themes remains the same as in the second subperiod, indicating a continuous evolution of themes from the second subperiod until the final one studied. Furthermore, most thematic areas exhibit increasing evolution regarding the number of documents (dimensions of the spheres). This signifies a growth in the number of documents compared to the previous period, indicating the sustained interest of the research community in these themes.

Regarding the thematic composition of each thematic area, the following observations can be made:

1. The themes TIMBER-STRUCTURES and DESIGN (undefined themes) evolve into motor, basic, highly developed, and emerging or disappearing themes in the second subperiod.
2. TIMBER-STRUCTURES and DESIGN are the origins of the theme CONNECTIONS, a motor theme in the second and third subperiods.
3. Two thematic areas consist of motor or basic themes throughout all the subperiods:
    - LYFE-CYCLE (motor theme) evolves into ENERGY-PERFORMANCE (motor theme) and CONSTRUCTION (basic theme).
    - CONCRETE (basic theme) evolves into CIRCULAR-ECONOMY (motor theme).
4. Only one thematic area comprises a highly developed theme in all the subperiods: HYGROTHERMAL-PERFORMANCE evolves into BUILDING-ENVELOPE.
5. Four thematic areas consist of motor or basic themes and an emerging or disappearing theme:

- CONNECTIONS (motor theme) evolves into CONNECTIONS (motor theme), ENERGY-PERFORMANCE (motor theme), COMPOSITES (motor theme), and FLOORS (emerging or disappearing theme).
- NUMERICAL-MODELING (motor theme) evolves into SEISMIC-PERFORMANCE (emerging or disappearing theme) and COMPOSITES (motor theme).
- INDUSTRIALIZED-CONSTRUCTION (basic theme) evolves into CONSTRUCTION (basic theme) and FLOORS (emerging or disappearing theme).
- MODELING (basic theme) evolves into MODELING (emerging or disappearing theme), COMPOSITES (motor theme), CONSTRUCTION (basic theme), and CONNECTIONS (motor theme).

6. Only one thematic area comprises a highly developed theme, two motor themes, and an emerging or disappearing theme: THERMAL-PERFORMANCE (highly developed theme) evolves into ENERGY-PERFORMANCE (motor theme), CIRCULAR-ECONOMY (motor theme), and FLOORS (emerging or disappearing theme).
7. Only one thematic area consists of three emerging or disappearing themes and two motor themes: WALLS (emerging or disappearing theme) evolves into BUILDING-ENVELOPE (highly developed theme), COMPOSITES (motor theme), CIRCULAR-ECONOMY (motor theme), MODELING (emerging or disappearing theme), and SEISMIC PERFORMANCE (emerging or disappearing theme).

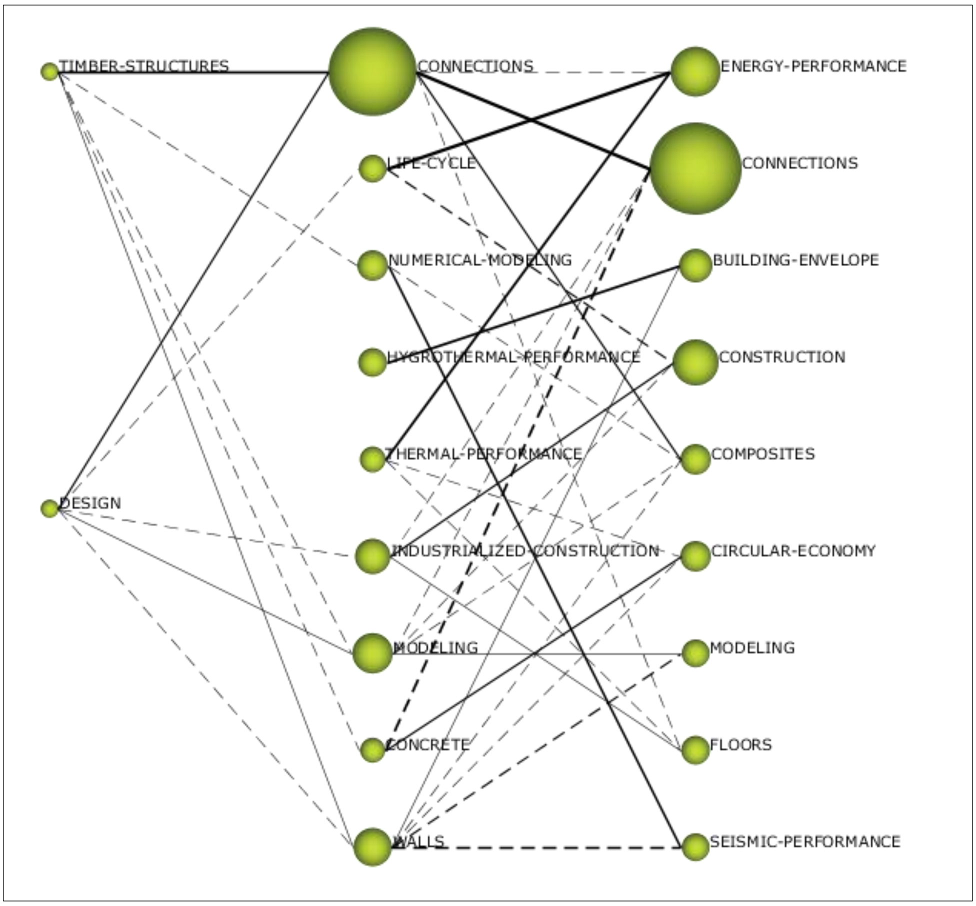


Figure 14. Thematic evolution network of the research field from 1990 until 2023.

4. Analytical Description by Subperiod

According to the insights provided by the bibliometric analysis, an analytical description of the leading research topics and current challenges is outlined as follows:

4.1. Superiod 1990–2004

It demonstrates a notable inclination toward studying timber-framed panel walls' design and structural behavior. These walls are commonly employed as the primary bearing capacity elements in constructing prefabricated timber structures [78]. Furthermore, there is a noticeable growth in the development and utilization of simulation tools, such as FEM, to analyze the behavior of timber structures. Overall, this period denotes a significant advancement in the research and exploration of prefabricated timber structures, beginning the way for further improvements and innovations.

4.2. Superiod 2005–2019

The utilization of CLT as a prefabricated component in medium- and high-rise buildings became critical, and it worked hand-in-hand with connections. While concrete is still used, it assumes a different role in this context as a material that complements emerging prefabricated timber structures, such as hybrid systems. It is also clear that model approaches remain an essential tool for comprehending the behavior of timber structures. Two fundamental concepts emerge within the construction industry: life cycle and industrialized construction. Unquestionably, one of the most significant advantages associated with employing prefabricated timber systems in construction lies in reducing costs, labor, and time, and the subsequent decrease in carbon emissions and their impact on the structure's overall life cycle.

4.3. Superiod 2020–2023

During this subperiod, the researchers kept attracting attention by exploring the structural behavior of prefabricated and modular timber buildings (mass timber and composite elements). Vital aspects involved examining new wood species that exhibited potential for being employed in the manufacturing process of CLT and innovative proposals for developing connections. Furthermore, attention was being given to improving the energy efficiency of timber buildings by enhancing building envelope systems. There were ongoing research studies on prefabricated timber walls (light timber-framed and mass-timber external assemblies) due to wood's susceptibility to humidity and temperature changes. Apart from these matters, the construction industry was also witnessing the emergence of the circular economy concept as a prominent topic. Prefabricated timber technologies possess various qualities that make them suitable for implementing a circular construction approach. According to the existing literature, these qualities include a faster construction process, reduced pollution, and the potential for material reuse and recycling.

Finally, another significant change observed in the timber construction industry during this period was the application of new digital technologies into industrialized construction practices. There was a clear indication of interest in the extensive application of technology to provide a holistic framework for designing, managing, manufacturing, and producing prefabricated/modular timber buildings.

5. Conclusions

The primary contribution of this study is the identification of relevant topics, emerging trends, and prospective pathways in the research of prefabricated and modular timber structures through the analysis of strategic diagrams and cluster networks with the aid of the SciMAT software.

The thematic evolution revealed an initial interest in understanding the structural behavior of timber buildings with light structures. This interest was achieved using numerical factors, analytical models, and experimental tests. The rationale behind this focus was based on the fact that this system constituted a substantial percentage of the houses constructed in North America, Australia, New Zealand, Japan, and Europe [36]. Subsequently, with the introduction of mass timber products and composite elements, the design and construction methods demanded increased concern in detailing critical elements and new planning methods. Consequently, research efforts were primarily concentrated on the study of two critical elements, namely, connections (which impact the structural functionality, manufacturing, and construction of the entire building system) and the building envelope systems (which safeguard the timber building structure from undesirable weather conditions during the construction phase and enhance the energy efficiency of timber buildings during their operational lifespan). Despite the increasing demands and challenges, the number of CLT modular projects achieved a remarkable milestone in 2017, reaching its peak with the completion of 26 buildings [22].

Furthermore, the analysis results indicated a strong correlation between design and prefabricated and modular timber structures. This correlation was observed from the first subperiod and represents potential opportunities for future research. It was found that prefabrication and modularization offer numerous advantages, such as flexibility in design and the ability to customize and standardize constructive elements. However, Ribeiro et al. [79] identified specific barriers associated with prefabrication. One such barrier is that architectural design often fails to consider the modular construction aspect, primarily due to aesthetic limitations. Similarly, Svatoš-Ražnjević et al. [80] pointed out that only some modular timber projects differ from the traditional rectangular and orthogonal footprints. From the publications analyzed, the modular design approach has predominantly been applied to houses rather than large-scale projects, potentially due to the limited exposure to modular technology in the popular literature and timber databases.

In addition, the analysis of thematic clusters and trends revealed that two factors influence the development of prefabricated and modular timber structures:

- Circular economy. Researchers have shifted their focus towards the reusability and efficiency of prefabricated elements. Prefabricated timber construction is characterized by utilizing large-format building elements and the associated logic of joining them together [16]. This characteristic makes it suitable for disassembly, reuse, and recycling. Therefore, adopting strategies and measures that reduce the carbon footprint, minimize waste, and increase the life cycle of structures aligns with the principles of circular construction. To this end, various initiatives have been developed, exemplified by the MAI-Ivalsa Modular House. This environmentally sustainable system of prefabricated housing modules employs reused CLT for the load-bearing structure, allowing for the prefabrication of components at one site and their successful transportation to another [81]. Another example is the Collegium Academicum IBA, the first multi-story modular timber student residence that offers significant spatial flexibility through simple modular pieces that can be easily disassembled and recycled [82,83]. Additionally, a ten-square-meter prototype utilizing a fully modular precast lightweight engineered timber structural system, as developed by [84], has demonstrated the potential of building-scale additive manufacturing with cost-effective materials to enable deconstruction and material recovery. Studies focusing on hybrid structures have recently begun incorporating assessment strategies such as design for disassembly or deconstruction (DfD). For instance, Grüter et al. [85] presented two case studies of modern residential timber hybrid buildings in Switzerland, employing digital tools to evaluate strategies that facilitate a circular design process for timber elements. These strategies specifically address the elements' start and end of life, thus serving as a solid foundation for future research. Similarly, Derikvand and Fink [86] proposed directions for future developments and advocated for DfD in timber–concrete composite (TCC) floors, emphasizing deconstructable connectors that enable material recovery and reuse as the preferred end-of-life scenario. These projects underscore the importance of integrating sustainable practices into the design and construction processes. Despite the recent release of a standard by the International Organization for Standardization (ISO), which provides general rules for integrating design for disassembly and adaptability (principles of circular economy) into the service life of structures [87], few studies have, thus far, presented innovative solutions and designed buildings that fully address these strategies. From the literature content analysis focusing on connections and building envelope systems (as was established before, they are critical elements in the design and construction of prefabricated and modular timber structures), only one study stands out as it introduced a novel reversible mass timber connector for prefabricated systems [88] while another explored the design and construction of fully prefabricated façade components to reduce materials and production energy [89].

- Digital technologies. Digital architecture, computer science, engineering informatics, virtual reality (VR), and building information modeling (BIM) are critical in prefabricated and modular timber construction. Integrating these parameters into industrialized construction practices necessitates the implementation of automation in timber manufacturing. For instance, in Canada, there is a strong focus on integrating BIM information into the construction phase, specifically in the context of automated fabrication. A study by [90] delved into a BIM-based framework that aims to automate the machine capability evaluation of timber frame assemblies. This proposal highlights the system's ability to accurately determine whether a user-selected machine can effectively manufacture a construction product that has been pre-designed using BIM software. In the United Kingdom, the research developed by [91] adopted BIM models in the game environment (gamification) to facilitate the implementation of small- and medium-sized architectural and construction practices dedicated to visualization creation. The collected evidence showcases that combining a game-like platform and BIM can lead to simplified data delivery to clients, ultimately resulting in customer satisfaction, confidence, and increased sales of timber frame houses. According to [92], "*the level of automation is high in the initial stages of prefabrication but relatively low in the assembly stages, which require flexibility and human knowledge*." To address this, some research groups are focused on developing robotic systems. Robotic fabrication, directly connected to a precisely planned virtual model, significantly reduces the risk of construction mistakes and ensures high global precision. This results in a cost-effective and efficient construction system [93]. The literature reveals that robotic systems have enabled the construction of unconventional structures, such as the BUGA Wood Pavilion. Furthermore, companies like Weinmann and Randek have gained recognition for adopting these technologies in their processes [94]. Similarly, researchers in the United States have devised a simulation-based methodology to evaluate the automated assembly of wood frames through BIM, utilizing various robotic systems [95]. By employing simulation techniques, researchers can assess the effectiveness of different robotic systems in automating the assembly of timber frames.

However, among the selected papers, only a few studies delved into the practical implementation of these technologies. This can be attributed to the persistent obstacles that hinder the adoption of digital technology, such as the fragmented and disorganized nature of reverse supply chains, resulting in a lack of practical information sharing among stakeholders. Moreover, these supply chains' intricate and diverse nature renders the recreation of accurate (BIM) models representing the existing conditions often expensive or time-consuming. Additionally, actors involved may lack the necessary knowledge or skills to embrace certain technologies, further impeding their application [96]. Furthermore, establishing and improving manufacturing environments, which typically necessitate substantial investments, also pose a significant challenge in adopting these technologies.

Drawing from the results obtained in the investigation, it becomes evident that the market ratio of these construction technologies continues to evolve. This development highlights the interrelation of digital technologies in effectively supporting and facilitating advanced circular economy strategies in the design and construction processes. These strategies include supporting forestry, reducing expenses, shortening installation schedules, and ensuring a significantly cleaner and more regulated environment, which enhances workers' health and safety, as the operational processes are greatly minimized. However, it is essential to acknowledge a significant gap in research and knowledge surrounding these topics, which necessitates further exploration and understanding. Studies conducted in Austria and Australia focused on developing perception surveys and interviews of relevant industry stakeholders to gain insight into the barriers to the widespread application of digital technologies and circular strategies on prefabricated and modular timber construction. For instance, Santana-Sosa et al. [97] highlighted a lack of knowledge and experience, limited implementation of digital tools such as BIM, inadequate capacity of current infrastructure and procedures, and absence of standardization in design, planning, optimized construction management, and manufacturing. Similarly, in Australia, the study conducted by [98] identified a lack of regulations, performance concerns, limited application experience among local manufacturers and suppliers, inadequate regulatory and insurance policies, financing challenges, difficulty in incentivizing clients, and a shortage of a skilled workforce.

Considering the significance of these findings, it becomes crucial for multiple sectors to act:

- Reevaluating the regulatory framework is necessary to encourage research collaborations between countries, facilitating the transfer of specialized technology knowledge to the labor market.
- Open new research areas in the construction sector, contributing to the growth of existing scientific systems and advancing these fields.
- Implementing professional training programs in industries can promote competitiveness and employment opportunities.
- Integrating timber expertise, including designers, producers, and construction companies, at different stages of the construction process can further enhance the adoption of prefabricated and modular timber construction.
- Raising society's awareness and knowledge transfer of timber's potential, such as its safety, cost-effectiveness, adequate structural performance, and environmental aspects, can foster the acceptance of these technologies.

Ultimately, the findings of this research significantly contribute to the existing body of knowledge and serve as an initial comprehensive platform that supports further investigations of these construction technologies. Future research will explore the relationship between circular economy strategies concerning prefabricated and modular timber construction, such as design for disassembly/deconstruction (DfD) and design of adaptability (DfA).

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