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Longitudinal analysis of interorganizational collaborative networks of cross-laminated timber (CLT) construction

Interorganizational
collaborative
networks

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Abstract

Purpose – Cross-laminated timber (CLT) is an innovative construction material that provides a balanced mix of structural stiffness, fabrication flexibility and sustainability. CLT development and innovation diffusion require close collaborations between its supply chain architectural, engineering, construction and manufacturing (AECM) stakeholders. As such, the purpose of this study is to provide a preliminary understanding of the knowledge diffusion and innovation process of CLT construction.

Design/methodology/approach – The study implemented a longitudinal social network analysis of the AECM companies involved in 100 CLT projects in the UK. The project data were acquired from an industry publication and decoded in the form of a multimode project-company network, which was projected into a single-mode company collaborative network. This complete network was filtered into a four-phase network to allow the longitudinal analysis of the CLT collaborations over time. A set of network and node social network analysis metrics was used to characterize the topology patterns of the network and the centrality of the companies.

Findings – The study highlighted the scale-free structure of the CLT collaborative network that depends on the influential hubs of timber manufacturers, engineers and contractors to accelerate the innovation diffusion. However, such CLT supply collaborative network structure is more vulnerable to disruptions due to its dependence on these few prominent hubs. Also, the industry collaborative network's decreased modularity confirms the maturity of the CLT technology and the formation of cohesive clusters of innovation partners. The macro analysis approach of the study highlighted the critical role of supply chain upstream stakeholders due to their higher centralities in the collaborative network. Stronger collaborations were found between the supply chain upstream stakeholders (timber manufacturers) and downstream stakeholders (architects and main contractors).

Originality/value – The study contributes to the field of industrialized and CLT construction by characterizing the collaborative networks between CLT supply chain stakeholders that are critical to propose governmental policies and industry initiatives to advance this sustainable construction material.

Keywords Knowledge management, Innovation, Social network analysis, Supply chain management, Organizational learning, Construction technology

Paper type Research paper



Introduction

Cross-laminated timber (CLT) is one of the main innovative products of the massive (i.e. mass) timber construction approach, which can provide a sustainable building material alternative for traditional structural systems. CLT is typically a panelized product that is manufactured by gluing an odd number of alternating right-angle layers of lumber boards (Wieruszewski and Mazela, 2017). As such, CLT delivers high levels of structural stiffness that allows a wider use of timber in low and mid-rise buildings (Harte, 2017). In addition, CLT is one of the recent promising innovations in the construction industry as a sustainable machinable building material (Ahmed and Arocho, 2020) that delivers more value to building owners and developers. CLT and other mass timber products were found to reduce the building embodied carbon by 22%–50% compared with concrete structures (Puettmann *et al.*, 2021). CLT enables a creative convergence of digital design and fabrication, which results in significant efficiencies and expands the manufacturing possibilities to deliver unique and customized building designs (Muszynski *et al.*, 2017).

The development of CLT and its delivery within construction projects require sophisticated interorganizational collaborative networks. Compared with commodity wood products, CLT construction enables and requires higher levels of collaboration between the supply chain players (Quesada-Pineda *et al.*, 2018). Regardless of the adopted project delivery method, it is common to observe strong collaboration in mass timber construction projects between the team members, including the architects, engineers, contractors and manufacturers (Muszynski *et al.*, 2017). CLT product development and usage depend on the “industry culture” (Gosselin *et al.*, 2018) that encompasses the accumulated partnerships, knowledge, experience and innovation of the CLT supply chain stakeholders. The innovation creation and diffusion within an industry are heavily dependent on the collaborative interorganizational networks between the industry stakeholders in a variety of industries (Ahuja 2000; Whittington *et al.*, 2009; Acemoglu *et al.*, 2011; Kolleck, 2013; Farré-Perdiguer *et al.*, 2016) and in the construction industry (Zhang *et al.*, 2013; Xue *et al.*, 2018; Dou *et al.*, 2020).

This study presents a descriptive longitudinal analysis of the collaborative networks between the main supply chain stakeholders of the CLT construction industry. The study characterizes the interorganizational collaborative networks between the various architecture, engineering, construction and manufacturing (AECM) firms that collaborate over time and between projects to share knowledge and deliver CLT building systems. Analyzing these collaborative networks is crucial as they constitute the venues for knowledge sharing and innovation diffusion of innovative products (Powell *et al.*, 1996; Ahuja 2000; Dewick and Miozzo, 2004; Taylor and Levitt, 2007; Taylor *et al.*, 2009; Acemoglu *et al.*, 2011; Xue *et al.*, 2018; Dou *et al.*, 2020; Zhang *et al.*, 2020). The study involved the acquisition of data from 100 CLT projects in the UK for a descriptive social network analysis of the underlying CLT collaborative networks and the unique attributes of the different types of AECM firms. The paper is organized into five main sections. First, a review of relevant literature on collaborative construction network modeling and CLT construction is presented. Second, the study research methodology is detailed by describing the acquired data and the applied social network analysis. Third, the results of the analysis are presented. Fourth, the main insights and the implications of the study are discussed.

Previous research

A comprehensive literature review was conducted to determine the current state of knowledge regarding the stakeholders, their collaboration networks, innovation diffusion and market attributes of CLT construction products. Using Google Scholar and Scopus as the

primary search engines, keywords such as “CLT”, “cross laminated timber”, “stakeholders”, “innovation”, “diffusion”, “collaboration” and “market” were systematically used to identify relevant academic works. [Table 1](#) summarizes the scope, methodology and regional relevance of the 22 previous relevant studies.

The synthesis of the relevant literature revealed the following knowledge themes around the stakeholders, their collaborations, market attributes and innovation:

- Architects and timber manufacturers were the most studied stakeholders in the literature. In some studies, they were studied as part of the delivery teams of single or multiple case study projects ([Fraser, 2017](#); [Gosselin et al., 2018](#); [Hamalainen and Salmi, 2022](#); [Orozco et al., 2023](#); [Penfield et al., 2022](#)). Architects were the sole focus of other studies to study their awareness and perception of CLT ([Laguarda Mallo and Espinoza, 2015](#)), and model their adoption tendency of CLT products in their designs ([Zhong and Gou, 2023](#)). On the other hand, timber manufacturers were the sole focus of other studies to study their perception of CLT practices and prospects

Reference	Scope	Methodology	Region
Engström and Hedgren (2012)	Stakeholders, innovation	Multiple case studies, qualitative analysis	Sweden
Mahapatra et al. (2012)	Innovation, market attributes	Qualitative analysis	Germany, Sweden, UK
Falk (2013)	Innovation	Systematic review	Multiple
Laguarda Mallo and Espinoza (2015)	Stakeholders, market attributes	Survey, qualitative analysis	USA
Jones et al. (2016)	Stakeholders, innovation	Qualitative analysis	UK
Fraser, (2017)	Stakeholders, innovation	Survey, qualitative analysis	Sweden
Lindgren and Emmitt, (2017)	Innovation	Case study	Sweden
Quesada-Pineda et al. (2018)	Market attributes	Multiple case studies, qualitative analysis	Western Europe
Schwarzmann et al. (2018)	Market attributes	Interviews, qualitative analysis	German-speaking Alpine Region
Gosselin et al. (2018)	Stakeholders, collaborations	Multiple case studies, qualitative analysis	Europe
Riggio et al. (2020)	Innovation	Case studies	North America
Brandt et al. (2021)	Market attributes	Empirical modeling	Western USA
Poirier et al. (2021)	Innovation, collaborations	Case study	Canada
Staub-French et al. (2021)	Innovation, collaborations	Case study	Canada
Penfield et al. (2022)	Stakeholders, market attributes	Survey, quantitative analysis	USA
Hamalainen and Salmi, (2022)	Stakeholders, innovation	Interviews, qualitative analysis	Finland
Svatoš-Ražnjević et al. (2022)	Market attributes	Quantitative analysis	Multiple
Ilgin et al. (2023)	Stakeholders, market attributes	Interviews	Multiple
De Araujo and Christoforo, (2023)	Stakeholders	Systematic review and sectorial survey	Multiple
Orozco et al. (2023)	Stakeholders, collaborations	Quantitative analysis	Multiple
Zhong and Gou, (2023)	Stakeholders, innovation	Empirical modeling	China
Ilgin and Karjalainen, (2024)	Market attributes	Interviews	Finland

Source: Author's own creation

Interorganizational collaborative networks

Table 1. Previous studies on CLT construction stakeholders, collaborations, innovation diffusion and market attributes

(Ilgin *et al.*, 2023) and the current and project global production capacity (De Araujo and Christoforo, 2023). One study (Jones *et al.*, 2016) recognized the role of contractors and engineers in the material selection as well as their reliance on other more influential stakeholders to explore design options beyond the conventional methods. Only a single study (Engström and Hedgren, 2012) analyzed the client's role in industrialized building innovations and highlighted their cognitive barriers toward such innovations and preference for safer decisions to use conventional construction methods.

-
- Few studies analyzed the nature and dynamics of collaborations between the CLT stakeholders, and they were limited to project collaborations, not industry long-term collaborations. Gosselin *et al.* (2018) interviewed 27 stakeholders and proposed a conceptual model of their collaboration relations in delivering structural timber projects and developing this emerging industry. Poirier *et al.* (2021) performed a three-year case study of a tall wood structure in Canada to showcase the use of government-industry-academic collaboration to facilitate innovative design processes. The same case study was analyzed in another paper (Staub-French *et al.*, 2021) and highlighted the clustered collaborations within the project team to innovate in the building connections and the used timber material. Finally, Orozco *et al.* (2023) presented a descriptive analysis of a large sample of multiregional sample of mass timber construction stakeholders and presented project network, stakeholder network and stakeholder country network views of the dataset to provide a visual identification of the existing collaboration clusters. However, the study did not involve in-depth network analysis to quantitatively assess the topologic characteristics of the network that can affect innovation diffusion.
 - About half of the relevant studies have studied the market adoption barriers, demand characteristics and supply capacities of CLT and other mass timber products. The most commonly identified CLT adoption barriers by researchers were (Ilgin *et al.*, 2023; Ilgin and Karjalainen, 2024; Laguarda Mallo and Espinoza, 2015; Mahapatra *et al.*, 2012; Penfield *et al.*, 2022; Quesada-Pineda *et al.*, 2018; Schwarzmann *et al.*, 2018): building code compliance, cost, design expertise, sufficiency of wood supply, production quality, lack of integrated project delivery (IPD) and construction expertise. A novel study (Orozco *et al.*, 2023) analyzed the demand characteristics of CLT and advanced timber structures by examining the architectural designs and structural systems of 350 timber multistory buildings from multiple countries and concluded the following: (1) a rectilinear building grid layout was used in most of the sampled projects, and (2) other conventional materials (steel and concrete) were used to allow for more design freedom and fulfill stringent structural performance requirements. On the supply side, another study (Brandt *et al.*, 2021) found that the production capacity of the US Northeastern lumber industry is greater than the local timber building demand and can satisfy the construction needs of the whole Western regions of the USA and Canada.
 - Previous studies investigated CLT and mass timber innovation by analyzing their adoption models, product-process innovation approaches and innovation diffusion. First, CLT adoption was analyzed from the perspectives of decision-making theory, organizational information processing and behavioral preconditions. Engström and Hedgren (2012) identified cognitive rules and organizational barriers that impeded the tendency of construction clients to adopt timber-industrialized construction innovations. Jones *et al.* (2016) applied the COM-B behavioral modeling system

(capability, opportunity, motivation and behavior) to conclude that designers and architects were the most stakeholders driven by the motivation to adopt such innovative products. Second, a group of studies used a case-based approach to analyze the innovation of timber products (Riggio *et al.*, 2020) and the implemented process innovations to design and construct innovative timber projects (Poirier *et al.*, 2021; Staub-French *et al.*, 2021). Third, the diffusion of the CLT innovation was analyzed through well-established theoretical frameworks and qualitative sample-based induction. Mahapatra *et al.* (2012) found that the diffusion of advanced timber multistory systems was more enabled in Sweden, compared with Germany and the UK, because of the supportive regulations and positive public and professional perceptions. Fraser (2017) applied the innovation diffusion theory and suggested that central stakeholders such as contractors, architects and engineers have a critical role in popularizing the CLT systems, especially in the early adoption phases. Lindgren and Emmitt (2017) applied a longitudinal analysis of the diffusion of an innovative multistory timber system and concluded that its market deployment was affected by the cultural attachment to traditional material, the regulatory support, the product complexity, the financial burden of the practice change and the maturity of the product value proposition. Hamalainen and Salmi (2022) highlighted the current fragmented structure of the CLT business network despite the increased collaboration levels and emphasized the role of collaborations with architects and engineers to increase the diffusion of CLT products.

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The review of the relevant literature revealed some pressing research gaps. First, most of the previous studies limited their CLT development and implementation collaboration analysis to disconnected case studies without considering the linkage between these projects that allow the transfer of knowledge and diffusion of innovation. Second, the stakeholders were analyzed in isolation without considering their dynamic relations and roles in their bigger industry-wide collaboration network. Finally, most of the stakeholder roles and their collaborations were qualitatively analyzed, which impeded the additional research needed to relate them to the innovation diffusion dynamics and devising the necessary public policy to support this sustainable building material. As such, there is a need for additional longitudinal studies of the evolution of CLT collaborative networks over time, with a larger sample of the industry stakeholders and in-depth quantification of their roles (Hamalainen and Salmi, 2022).

Researchers investigated the collaborative networks in construction projects, mostly using social network analysis (SNA), and their role in improving the performance of project teams, the diffusion of their knowledge and the innovation of new processes and materials. Pryke (2004) proposed using SNA to study the interdependencies between the project actors and their knowledge exchange in construction projects. Another earlier study was conducted by Dewick and Miozzo (2004), where they assessed the impact of interorganizational network relations on the introduction and diffusion of sustainable technologies in the Scottish housing sector. Taylor and Levitt (2007) contrasted the case studies of three 3D CAD technological innovations for understanding innovation in project networks. Rutten *et al.* (2009) reviewed multiple literature domains to identify the role of system integrators and various network factors in new product development, alliance formation and innovation. Taylor *et al.* (2009) studied the impact of reciprocal interorganizational relations on organizational learning in project collaborative networks. Chinowsky *et al.* (2010) used SNA to study the inner organizational networks of engineering firms by relating multiple graph metrics to the firms' leadership and collaboration interpretations. Chinowsky *et al.* (2011) evaluated the

effectiveness of a project management team by measuring the alignment between the team's stakeholder knowledge exchange and their task communication requirements. [Zhang et al. \(2013\)](#) analyzed the dependency between the flexibility of IPD teams on their ability to share tacit knowledge. [Lin \(2014\)](#) used SNA to study the authority, information exchange and knowledge consultation networks of an infrastructure project by interpreting the network's overall topology, the existence of subnetworks and the position of the project stakeholders. [Xue et al. \(2018\)](#) used the SNA density and centrality metrics of a project case study to interpret the level of collaboration, hence qualitatively assessing the innovation level in the project. Another research group used the graph properties of core-periphery structure and subgroups to study the knowledge transfer topologies in architectural, engineering and construction (AEC) project teams ([Garcia et al., 2021](#)), and to study the impact of the inconsistencies between a project's organizational and technical networks on the team collaboration efficiency ([Zhao et al., 2021](#)). Few recent studies have investigated the collaborative networks in the industrialized construction industry. [Zhang et al. \(2020\)](#) used SNA to analyze the sustainability collaborative network patterns of innovative sustainability in an industrialized construction project. [Dou et al. \(2020\)](#) studied the interorganizational diffusion of prefabricated construction technologies by analyzing the collaborative network of related patents in China.

Research objective and methodology

This study aims to analyze the structure and stakeholder roles of the collaborative networks of CLT projects to provide a preliminary understanding of the knowledge diffusion and innovation process of CLT construction. As shown by the literature review, most of the previous studies focused on studying the collaborative and communication networks within a single construction project, which ignored the knowledge transfer between the projects and the long-term supply chain collaborations among the industry stakeholders. The study addresses this research gap through a longitudinal analysis of the collaborative network that has developed between the AECM firms involved in a sample of CLT projects.

Data collection and processing

The study data was acquired from an industry report prepared by [Waugh and Thistleton \(2018\)](#) and funded by the Softwood Lumber Board and Forestry Innovation Investment. The report is entitled "100 UK CLT Projects" and showcases a wide array of CLT projects between the years 2005 and 2018. This data has been used in previous studies ([Orozco et al., 2023](#); [Svatoš-Ražnjević et al., 2022](#)) and was selected for this research due to the diversity of its sampled projects and the inclusion of sufficient data on their design and stakeholders. The report is published in the form of an atlas, where one to two pages were dedicated for each project to share the following descriptive information:

- (1) general description of the project with information about its construction completion year, uses, owner and design parameters;
- (2) project visuals that include schematic drawings, project renderings and real photos;
- (3) abstract construction data related to construction time and budget for the CLT scope of some projects;
- (4) the project type, being either "Education", "Residential", "Commercial" and "Public and Civic";

-
- (5) the project team by sharing the company business names of the following stakeholders: architect, structural engineer, main contractor, timber engineer, timber contractor and timber manufacturers; and
 - (6) the structure type can be either “Pure CLT”, “Pure Timber” (CLT and other timber products) and “Hybrid” (timber and conventional building material like steel or concrete). As per the purpose of this study of analyzing the CLT stakeholders and their collaboration network, only the project team and its completion year.

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The report information was coded in a tabular format to capture the structure type and the collaborating team data for each project. First, a project data table was created to assign each project a unique identification number and provide the following data fields: year and the project team firms. It should be noted that some project teams involved multiple firms of the same stakeholder type, e.g. a large or complex project may involve multiple architects, engineers or main contractors. Second, the unique firm instances are filtered from the project records and assigned unique identification numbers. Third, a data matrix structure was created to relate each project (as rows) to the involved team stakeholder firm (as columns). There was a total of 261 project stakeholders involved in these projects, including 73 architecture, 58 structural engineering, 74 main contracting, 31 timber engineering, 10 timber contracting and 15 timber manufacturing companies. To perform the longitudinal analysis, the projects and their stakeholder firms were organized in four time periods. As shown in [Table 2](#), the four analysis periods were determined to have a similar number of projects as well as good representations of the structure types and the team stakeholders in each period. Previous longitudinal studies ([Garcia et al., 2021](#); [Lu et al., 2020](#)) arbitrarily selected the number of analysis periods for reasons that are unique to each analysis.

Social network analysis

SNA integrates methodologies and concepts from graph theory, sociology, computational techniques and data visualization to analyze the interdependence between the network structure, its implied behavior and the opportunities and impacts of its individual nodes (actors) and links (actor relations) ([Newman and Girvan, 2004](#)). SNA is a mixed data analysis technique that transforms numerical data into quantitative network and actor metrics that are interpreted into narrative explanations with the aid of qualitative graph visualization observations ([Yousefi Nooraie et al., 2020](#)). The use of SNA in analyzing the CLT industry collaborative networks is justified for the following reasons:

Period	1	2	3	4
Years	2005–2010	2011–2013	2014–2015	2016–2018
Projects	28	21	27	24
Architects	26	20	26	22
Main contractors	28	17	22	22
Structural engineers	19	19	24	23
Timber contractors	4	4	6	6
Timber engineers	11	15	15	14
Timber manufacturers	3	5	10	10

Source: Author’s own creation

Table 2.
Longitudinal
organization of the
analyzed projects
and their team
stakeholders

- economic actions of individuals and businesses are not taken in isolation but rather emerge from the surrounding social network (Gulati, 1998);
- the overall network dynamics and individual actor behaviors are dependent on the network's global structure (supply chain configuration) not the dyadic (project) relations of the actors (Farré-Perdiguer *et al.*, 2016); and
- the multilevel approach of SNA to analyze the network topological dynamics and the influence of individual actors in the network (Gnyawali and Madhavan, 2001).

The researchers used Gephi (Bastian *et al.*, 2009), an open-source graph and network analysis that provides an intuitive user interface to analyze and visualize complex and large graph data sets.

The CLT collaborative network data is initially modeled as a two-mode affiliation graph (Wasserman and Faust, 1994) that is made up of relations between two node sets: projects and companies. This two-mode graph is modeled as $G_{2m} = (P, C, L)$, where: $P = \{P_1, P_2, \dots, P_n\}$ is a subset of the graph nodes representing the studied projects ($n = 100$); $C = \{C_1, C_2, \dots, C_m\}$ is a second subset of graph nodes representing the project team companies ($m = 261$); and $L = \{L_1, L_2, \dots, L_g\}$ is a set of the non-directional edges (relations) between the projects and the companies. In total, the complete network graph included 361 nodes ($n + m$) and 636 edges, which represent all the projects, the companies and their relations. This complete network was then longitudinally filtered into four smaller networks representing the analysis time periods of this study. Figure 1 shows the filtering processes and the graph attributes of the resulting four collaborative networks.

To performance the SNA, the project-company two-mode network G_{2m} is transformed into a one-mode company-company collaboration network using the network transformation technique (Borgatti and Everett, 1997). As shown in Figure 2, this network transformation results in:

- the removal of the project node set and its links with the company set from the network; and
- creating direct links between the companies that are indirectly connected in the two-mode network through a project node.

It should be noted that if two companies collaborate on more than one project, their link in the one-mode network will signify this repeated collaboration by increasing the weight value of the link. For example, the link between companies C_4 and C_5 in the transformed network has a value of 2 to represent their repeated collaboration. To summarize, the outcome of the network transformation was modeled as a graph $G_{1m} = (C, L, W)$, where: $C = \{C_1, C_2, \dots, C_m\}$ is the set of graph nodes representing the project team companies ($m = 261$); $L = \{L_1, L_2, \dots, L_c\}$ is a set

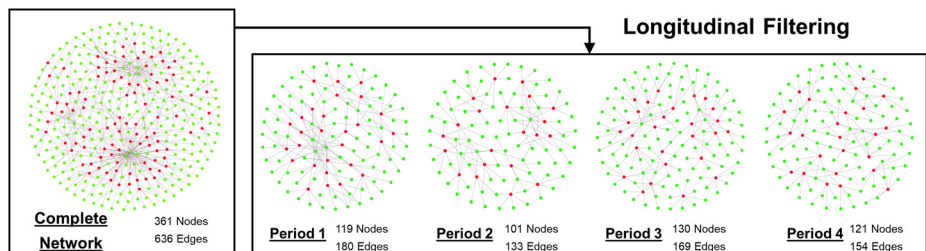
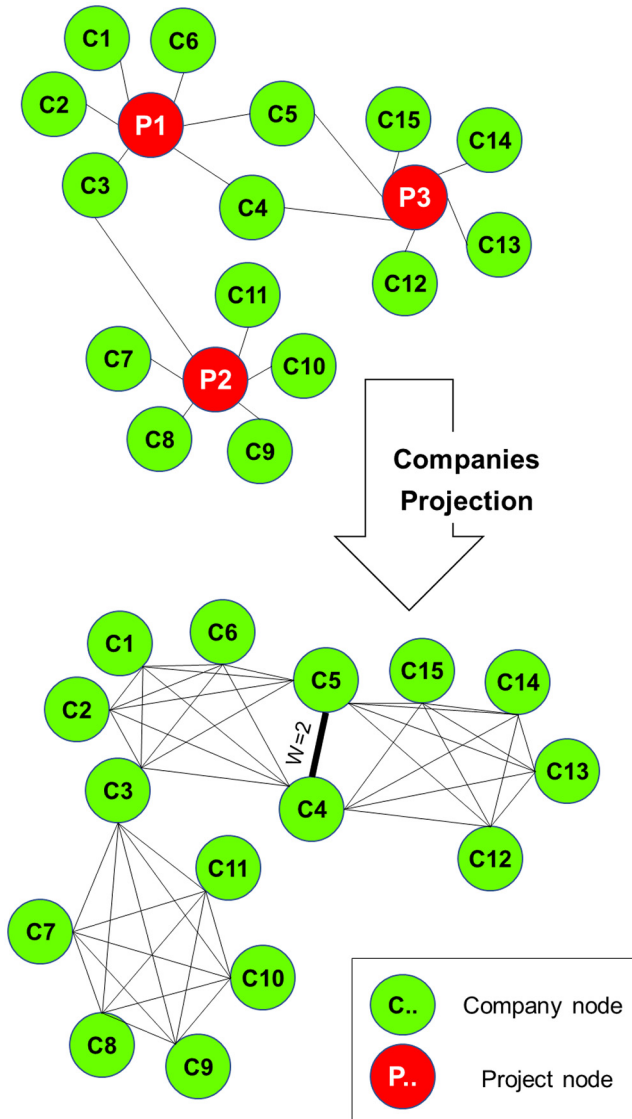


Figure 1.
The longitudinal filtering of the complete collaborative network

Source: Author's own creation



Source: Author's own creation

Figure 2.
Network projection:
transformation of a
multi-mode project-
company network
into a single-model
company-only
network

of the nondirectional edges (relations) between the companies; and $W = \{W_1, W_2, \dots, W_c\}$ is a set of the edge weights.

The adopted SNA mixed-method approach for analyzing the CLT collaborative networks depended on qualitatively assessing their graph visualizations and quantitatively evaluating their whole-network topology and node ego-centric metrics (Kolleck, 2013). The modeled social networks were visually analyzed to reveal latent characteristics of the CLT collaborative networks and to understand the dynamics of knowledge creation and diffusion

(Correa and Ma, 2011). Force-directed layout visualizations of the networks were used to expose the network clusters (also called communities), structural holes (gapes between the network clusters), central actors (most connected centrally-positioned nodes) and bridging connections between the network clusters (Venturini *et al.*, 2021). In addition to network visualization, two sets of SNA quantitative metrics were used (Chinowsky *et al.*, 2010; Lin, 2014; Provan *et al.*, 2007): network-level metrics to analyze the network topology attributes and node centrality metrics to analyze the roles of CLT stakeholders. These metrics and their calculations are explained in detail by (Wasserman and Faust, 1994). The following sections share more details on these two SNA metric sets.

Network-level metrics are used to measure different aspects of the collaborative network topology and structure that can help to infer possible enablers and obstacles for collaborative innovation diffusion (Zhang *et al.*, 2020). The following list compiles the network-level metrics and shares the reasoning for their use in this analysis:

- *Average weighted degree*: This metric calculates the average of the weighted degrees of all the nodes in the network, where the weighted degree of a node is the summation of the weights of all its links with other nodes. Average weighted degree is generally used to measure the connectedness of a network, and it is used in this study to measure the level of repeated collaborations between the companies.
- *Weighted degree variance*: This metric helps to assess the variability of the network node degrees. When considered together with the average weighted degree, the network degree distribution can be analyzed. A high value of weighted degree variance indicates increased heterogeneity of the company collaboration levels in the network and a faster speed of knowledge diffusion (Manshadi *et al.*, 2020).
- *Centralization*: It is an indication of the concentration of the links across the nodes in the network, i.e. a hint of the existence of a star-like network structure where most of the companies are collaborating with one or few focal companies. The centralization value ranges between 0 (a circular graph) and 1 (a perfect star graph with one focal node).
- *Density*: This metric calculates the ratio of the existing node links L_c to the total number of all possible links that can connect all network nodes. The density value ranges between 0 (a completely disjointed network with no links) to 1 (a complete network with all possible links). Graph density is an indication of the close information-sharing relations across the network (Xue *et al.*, 2018).
- *Modularity*: The modularity of a network is a metric of its structure segregation by grouping the network nodes into clear modules or communities. The modularity metric is a scalar value between -1 and 1 , which is maximized with the increased link density within the communities and the sparse connections between these communities (Blondel *et al.*, 2008).
- *Transitivity*: This network metric relates to the notion that “a friend of a friend is a friend” and assesses the existence of such transitive relations in the network. Transitivity is measured using the average clustering coefficient of all network nodes (Hardiman and Katzir, 2013). The clustering coefficient of a node equals the ratio of the number of edges between its neighbors to the maximum possible number of edges between these neighbors. Network transitivity is an indicator of the network subcommunity structure that is useful in understanding diffusion dynamics (Acemoglu *et al.*, 2011).
- *Average path length*: It measures the average distance (i.e. the number of links) on the shortest paths between all pairs of network nodes. This metric is a proxy measurement

of the delay of information diffusion within the network (Lu *et al.*, 2020), as shorter path length implies faster innovation diffusion and technology adoption.

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Three node centrality metrics were used to analyze the influence traits of the CLT stakeholders and those with significant hub, gatekeeping and pulse-taking roles in the analyzed collaborative networks. These centrality metrics describe the companies' locations in the network from different prominence perspectives, with the goal of assessing their coordination role in the network (Hossain, 2009) and access to innovation information and knowledge capital (Whittington *et al.*, 2009). These centrality metrics were commonly used in previous studies: degree centrality, betweenness centrality and closeness centrality (Freeman, 1978). The centrality percentile rankings are calculated for each company and the average percentile rankings of each stakeholder group (architects, main contractors, structural engineers, timber engineers, timber contractors and timber manufacturers) are also calculated. Furthermore, nodes with statistically high values of these degrees, betweenness and closeness centralities are identified as the network hubs, gatekeepers and pulsetakers, respectively (Helbling and Anderson, 2016). The following list shares these centrality metrics and their use in identifying the company roles:

- *Degree centrality*: It is the simplest form of measuring the importance of a network node by counting its links to other nodes. In this study, degree centrality measures how active a company was in delivering CLT projects and its collaboration spread between the other companies. A company is identified as a network hub if its degree centrality is at least one standard deviation above the network mean degree centrality. Network hubs gain their prestige through the generation of most of the collaborative knowledge and the control of its diffusion.
- *Betweenness centrality*: This metric is concerned about how close a network is to all other nodes that are not directly connected to each other. The betweenness centrality of a node is calculated as the number of times this node is located on the shortest paths (geodesic distances) between all node pairs in the network. Companies with high betweenness centrality can influence the collaborative network as "brokers" of information exchange and knowledge diffusion between the network communities. A company is identified as a gatekeeper if its betweenness centrality value is above the network mean value by at least a standard deviation.
- *Closeness centrality*: Based on this metric, a network node is central if it can quickly interact with other actors (i.e. has short geodesic distances from other nodes). Its value is calculated for each node as the average of the inverse of its distances with other nodes. They do not rely on other actors for communicating information. Companies with high closeness centrality have access to most of the collaborative network without the dependence on other more connect companies. Such close companies are identified as pulsetakers (their closeness score is at least one standard deviation higher than the network mean), who can access information from different parts of the network without dependence on or the influence of network hubs or gatekeepers.

Results

Network topology

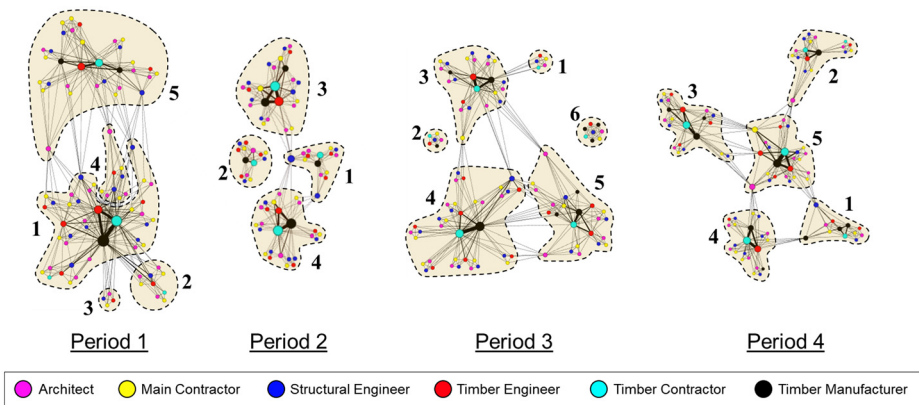
Graph visualizations and structural metrics were used to characterize the topology longitudinal change over time of the analyzed CLT collaborative networks. Figure 3 depicts the graph visualizations of the collaborative networks in periods 1–4, and the identified

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clustered communities of dense collaborations between the companies. The size of the node correlates with its average weighted degree value and the line thickness of a link between two nodes visualized their collaboration frequency (link weight). Figure 4 shows the corresponding change in the network structural metrics (degree distribution parameters, centralization, density, modularity, transitivity and average path length). The main longitudinal analysis observations of the network topology are as follows:

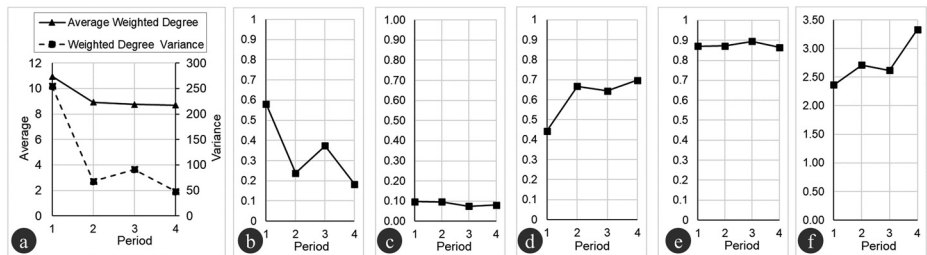
- The degree distribution indicated a decrease in the overall network connectedness and its variability between the collaborating companies. As shown in Figure 4(a), the connectedness of the network was higher in the first period and dropped significantly in the second period. This indicates a declining level of collaboration between the companies in terms of their co-involvement in one project or more, as measured by the average weighted degree values. However, contrasting these values to the minimum possible node degree (5 as there are at least 6 companies involved in each of the analyzed projects) confirms repeated collaborations of a single company with limited partners or a wider collaboration attitude with a larger pool of companies. On the other hand, the degree variance dropped

Figure 3. Longitudinal comparison between the topologies and communities of the collaborative networks of periods 1 through period 4



Source: Author's own creation

Figure 4. Longitudinal change of the collaborative network topology metrics over periods 1 through 4



Notes: (a) Avg. degree and variance; (b) centralization; (c) density; (d) modularity; (e) transitivity; (f) avg. path length

Source: Author's own creation

significantly between the 1st and the 2nd period, indicating a more flattened distribution of the node degrees in the network. This implies that some companies, initially, dominated the emerging CLT market as shown by their high connectedness in the first period.

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- Network centralization follows a similar trend to the degree of variance due to their common purpose to quantify the concentration of links across the nodes. This can be illustrated by the graph visualization in [Figure 3](#) which shows three specific companies (timber engineer, timber contractor and timber manufacturer) in community number 1 in the first period with a much higher degree of centrality than their peers and counterparts.
- The network density was very low in all periods, and it slightly decreased between the 2nd and the 3rd periods. As shown by its value being below 0.1, only 10% of the possible graph links were realized in the form of project collaborations between the companies. This implies a very sparse network due to the implicit multimode nature of the collaboration network with the existence of six company types, which limits the collaboration possibility between the companies of the same type (i.e. multiple architects in a project) to large or specialized projects.
- The modularity of the network increased by about 50% between the first and the second phase and showed a slower increasing trend afterward. Although a similar number of communities were detected in all periods (between 4 and 5 communities), their modularity quality in the first period was less due to the larger number of edges connecting the nodes beyond their communities. These cross-community links occurred due to the higher graph centralizations in the first period, as discussed before.
- The transitivity was high in all periods as measured by the average clustering coefficient, which confirms a high local clustering of the companies in the overall collaborative network over time. This can be attributed to the large teams (at least six companies) of the analyzed projects and their modeled lattice relations. Such a local cliquish structure is an expected phenomena for a typical social network and has been observed in other industries ([Scherngell et al., 2020](#)).
- The average path length of the collaborative network has increased by 42%. Theoretically, high transitivity and a short average path length are concurrently observed in social networks. However, the analyzed collaborative networks showed a fixed high transitivity value (local clustering) and did not follow the increasing trend of the average path length. This observed disparity between transitivity and the average path length can be a result of the increasing modularity of the network, where each community is internally cliquish but the cross-community separation between the companies is increasing.

Stakeholder roles

The roles of the six main project stakeholders were longitudinally analyzed by contrasting their centrality rankings and positions over the analysis time periods. The main result findings are:

- The “T” stakeholders of the collaborative network [Timber contractor (TC), timber engineer (TE) and timber manufacturer (TM)] have more influence as shown by their high centrality metrics ([Figure 5](#)). Timber contractors and timber manufacturers are the most influential and most connected in the network, and they showed similar trends in the three calculated centrality metrics. As shown

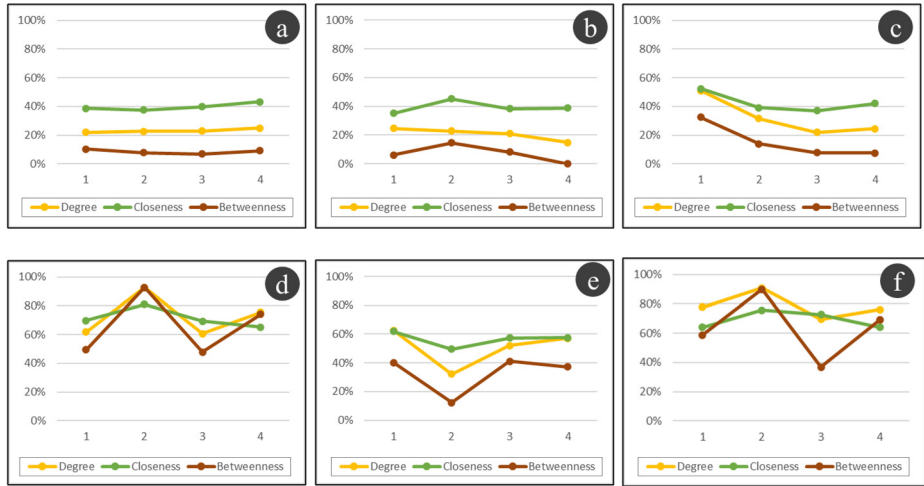


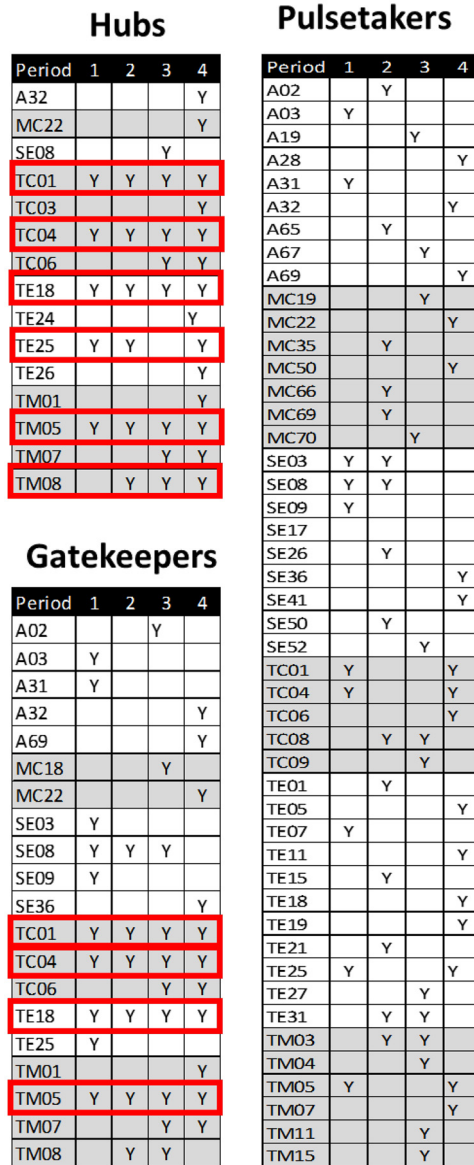
Figure 5.
Percentile ranking
longitudinal change
of the centrality
metrics for the six
company categories

Notes: (a) Architect; (b) main contractor; (c) structural engineers; (d) timber contractors; (e) timber engineers; (f) timber manufacturers

Source: Author's own creation

in Figure 6, the network hubs (identified by the degree centrality) were mostly dominated by the three timber-related stakeholders, and they tend to stay hubs over time (identified as hubs in at least three periods).

- The control of timber engineers and timber contractors on the network hubs has declined over time. In the first period, timber contractors and timber engineers represented 80% of the network hubs, as shown in Figure 6. This share declined to 58% in the last period, because more architects, main contractors and timber manufacturers became hubs.
- There is a disparity between the low centrality average percentile rankings and the influential roles of selective group of architects, main contractors and structural engineers. This means that smaller percentage of A, MC and SE companies are influential, compared to the timber-related companies (TC, TE and TM).
- There seems to be a negative correlation between the centrality of timber engineers and the other timber-related companies (TC and TM), as illustrated in Figure 5(d)–(f), timber contractors and timber manufacturers improved their degree and betweenness centrality in the second period but declined in the third period. On the other hand, timber engineers followed a reverse trend by declining in the second period and improving in the third period.
- Architects have maintained a stable centrality position in the network as measured by their degree, closeness and betweenness metrics. Architects had a stable degree centrality at around the 24th percentile of the stakeholders, a betweenness centrality at about 9th percentile and closeness centrality at about 40th percentile. Other stakeholders showed either a fluctuating or declining trend in their centrality metrics.
- The degree and betweenness centralities of structural engineers and main contractors have eroded but approximately maintained the same level of their closeness centrality



Source: Author's own creation

Figure 6.
The identified hubs,
gatekeepers and
pulsetakers in the
collaborative
networks of periods 1
to 4

[Figure 5(b) and (c)]. However, structural engineers experienced the largest decline by dropping around 20% in their degree and betweenness rankings in the network.

- The gatekeeping influence shifted over time from engineering companies to construction and manufacturing companies (Figure 6). In the first period, structural engineers and timber engineers represented 30% and 20% of the network

gatekeepers, respectively. However, this share dropped to only 9% for each of these engineering companies. On the other hand, the gatekeeper representation increased for main contractors (from 0% to 9%), timber contractors (from 20% to 27%) and timber manufacturers (from 10% to 27%).

- Overall, the percentage of companies in hub influence positions increased over time from 5% in the first period to 14% in the last period, as shown in [Figure 6](#). This observation is aligned with the network topology longitudinal analysis findings of decreasing degree variance and centralization.

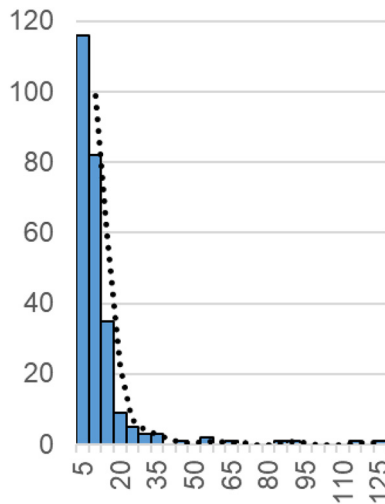
Discussion and research implications

Generally, networks can be classified into three network types: random, small world and scale-free ([Anderson et al., 2014](#)). Random networks are rare to observe in real-world social and organizational networks as they assume the randomness of link creation between the graph nodes. As such, random networks are usually used as the null hypothesis in categorizing a network and testing the attribution of its connectivity to randomness ([Perera et al., 2017](#)). Small-world networks, mathematically formulated by [Watts and Strogatz \(1998\)](#), mimic the natural social and cultural tendency of individuals and organizations to connect based on similar interests or attributes. These small-world networks are generally characterized by highly clustered structures and short path lengths, which creates an interesting disjunction between the reality of network actor closeness (also known as the six-degrees of separation) and the perception of network segregation. [Watts \(1999\)](#) established four conditions for a perfect small-world network to exist:

- (1) a large network size in the order of millions or billions;
- (2) a sparse network with low density;
- (3) a decentralized network as indicated by its low centralization and degree variance values; and
- (4) high transitivity of relations between the network neighbors.

Social networks can exhibit some or all these conditions, as the small-world phenomena cover a spectrum between random networks and regular networks (all nodes have the same degree). Scale-free networks were first introduced by [Barabási and Albert \(1999\)](#) as a model for real-world complex networks as a way to represent their gradual growth and preferential attachment (linkage) between the network actors. Scale-free networks are created by gradually adding actors, who prefer to connect with existing popular actors. As such, the degree distribution of the network nodes (actors) follows a power-law distribution, which implies the network's high centralization around a few nodes that have the most connections. It should be noted that scale-free networks can show some of the small-world network attributes, mainly the highly transitive and sparse topologies ([Aldrich and Kim, 2007](#)).

Although the analyzed collaborative networks displayed small-world structure features, they closely resemble a scale-free network structure that implies the vulnerability of CLT supply chain networks and improved knowledge diffusion. By examining the topology of the analyzed collaborative networks, it can be concluded that the CLT industry follows a scale-free network structure of collaboration and supply chain due to the observed low network density, moderate to high centralization and high transitivity. The complete network and its longitudinal subnetworks all showed a power-law distribution of their node degrees. As an example, [Figure 7](#) shows the skewed power-law degree distribution of the complete network, where 116 companies had a degree of 5 and only 8 companies had a degree above 45. There are



Source: Author's own creation

Interorganizational collaborative networks

Figure 7. Degree distribution of the complete collaborative network

two main implications of the scale-free network structure of the CLT industry. First, the industry supply chain may be subject to extreme disruptions due to its vulnerable centralization around few stakeholders (Kereri and Harper, 2019; Perera *et al.*, 2017), mainly the timber contractors, engineers and manufacturers. Second, the scale-free structure of the collaborative network enables efficient and fast knowledge diffusion due to the existence of influencing network hubs to accumulate and disseminate information rapidly (Lin and Li, 2010; Manshadi *et al.*, 2020; Tang *et al.*, 2010). As such, an interesting tradeoff has existed in the CLT construction collaborative networks between the supply chain vulnerability and the innovation diffusion tendency. As such public policies and strategies can minimize the supply chain vulnerability by supporting new timber manufacturing businesses while establishing industry excellence and research centers that act as knowledge transfer and innovation diffusion hubs.

The modularity of the analyzed collaborative networks provides an additional understanding of the collaboration and innovation diffusion of the CLT construction industry. Modularity, as a metric of the cohesion of formed collaboration communities, can contribute to either the diffusion or inhibition of product innovation. High modularity indicates the existence of cohesive communities with intracommunity connections that their inter-community connections, which foster the rapid adoption and development of technology by the members of the same community. On the other hand, low modularity indicates less cohesive communities, which enables the spread of technology adoption beyond individual communities to the whole group. As shown by the longitudinal analysis, the modularity of the collaborative network increased significantly between the first and the second analysis period. This implies that the industry was focused initially on the spread of the preliminary CLT innovation and transitioned to the collective learning and further development of the technology within cohesive communities (Taylor *et al.*, 2009). In addition, modularity is positively correlated with the threshold of adoption (Reich, 2015) as increased group cohesion levels are needed to overcome high-risk aversion attitudes toward technology. The low modularity in the first analysis period is a proxy indicator of the early risk-seeking attitude of the industry to develop the CLT construction.

This study highlights the conflicting propositions of previous studies on the role and influence of the supply chain stakeholders on knowledge transfer and innovation diffusion.

As confirmed by the results, the main hubs of the CLT construction collaborative networks were found to be the supply chain upstream stakeholders: timber manufacturers, timber contractors and timber engineers. This observation diverges from the common theoretical proposition of previous construction innovation studies (Chinowsky *et al.*, 2011, 2010; Dewick and Miozzo, 2004; Lin, 2014; Pryke, 2004; Taylor *et al.*, 2009; Taylor and Levitt, 2007; Xue *et al.*, 2018; Zhang *et al.*, 2013) that associated the hub position and influence to downstream supply chain stakeholders, the AEC companies. These studies analyzed intraproject collaborative networks, which eventually led to assigning the hub role to the architect and main contractor due to their “system integrator” responsibilities (Rutten *et al.*, 2009) to assemble and coordinate the design and construction of the project. However, collective industry innovation diffusion occurs in the interorganizational collaborative networks, where the hub company orchestrates the extraction and creation of valuable knowledge (Gulati, 1998). Industrialized construction, including CLT construction, requires frontloading of the project delivery, which provides a greater role and influence to upstream supply chain stakeholders. The industry hub position of timber manufacturers and contractors does not empower them to setup or change the organization of individual projects due to their lack of the contractual powers of the system integrators (i.e. architects and main contractors). However, their true influence is through mobilizing the accumulated knowledge and commercializing the product innovation (Dhanasai and Parkhe, 2006).

The results revealed interesting observations about the role differences and positions between the upstream and downstream supply chain stakeholders of the CLT industry collaborative networks. The supply chain downstream stakeholders (architects, main contractors and structural engineers) are generally the least connected in the collaborative networks. Despite their overall low centrality ranking, few of these downstream supply chain firms were more connected in the network to qualify as network hubs. This indicates that these hubs of architects, main contractors and structural engineers were successful in creating coalitions and partnerships together and with the upstream supply chain stakeholders. Regardless of their low degree of centrality, the influence of most downstream firms is through their roles as pulsetakers and being close to the most connected industry stakeholders, i.e. the upstream supply chain firms. On the other hand, upstream supply chain stakeholders include timber-related firms (timber contractors, timber engineers and timber manufacturers) and are the most connected in the analyzed collaborative networks. Although they are few, timber-related firms represented more than 50% of the hubs in all analyzed collaborative networks. The following are worthwhile specific and general observations on the roles and positions of the CLT collaborative network firms:

- Over time, more firms increased their connectedness and became influential hubs in the network. Considering the increasing network modularity and decreasing degree variance, these hubs play a centralized role in the network clustered communities to orchestrate the CLT innovation diffusion.
- The industry has decreased its dependence on structural engineers, timber engineers and timber contractors to advance the CLT technology, as shown by their share drop in the network hubs. The introduction of CLT in construction projects depended on the accumulated design and assembly experiences of engineers and timber contractors. Over time, such experiences were documented and shared in the form of industry standards and guidelines, which allowed the edge stakeholders of the supply chain (architects, main contractors and timber manufacturers) to collaborate directly and increase their influence.

The main observations of the study are summarized in [Table 3](#), which are used to propose the following practical and managerial implications:

SNA metric	Main observations	Interorganizational collaborative networks
Average weighted degree	Stakeholders are involved in repeated collaborations, but collaborations are maturing into coalitions	<p style="text-align: right;">Table 3. The study main observations from the calculated SNA metrics</p>
Weighted degree variance	The collaborations are becoming more equitable, with experiences being more accessible	
Centralization	The industry became less centralized around limited number of stakeholders	
Density	The network is naturally sparse due to the competitive segregated nature of the industry (i.e. it is less likely that two engineers will collaborate in a single project)	
Modularity	The industry has evolved into smaller communities of collaborations	
Transitivity	The temporary project-based setup of the industry results in a high local clustering in the overall collaboration network	
Average path length	The path of knowledge transfer has increased, confirming the creation of clustered communities of practice	
Degree centrality	Timber contractors and timber manufacturers were consistent collaboration hubs. Structural engineers became less centralized. Timber engineers were moderately centralized, while architects and main contractors had consistently least centrality	
Betweenness centrality	Timber contractors, timber manufacturers and timber engineers were the main gatekeepers in the network	
Closeness centrality	There less disparity between the stakeholders in this aspect, where the network pulsetakers were represented by all stakeholders	

Source: Author's own creation

- The CLT construction industry has matured into a set of defined “communities of practices” that represent different geographic and building usage clusters of the projects. For new companies engineering and contracting companies interested in this industry, they should focus on a limited number of these communities with similar specialized knowledge and design requirements. Also, government and academic institutions need to prevent the over-specialization of these communities and encourage cross-pollination of innovation and product development.
- CLT projects have increased the requirement for specialized knowledge, as shown by the rising influence of timber engineers and the declining influence of structural engineers. As such, structural engineering firms should acquire or establish internal timber engineering groups to infiltrate the growing CLT market.
- Upstream stakeholders (timber manufacturers, timber contractors and timber engineers) are an integral part of executing any public policies to increase the adoption of CLT, due to their strong hub and gatekeeping roles. However, the input into developing these policies can benefit from the inclusion of a diverse group of stakeholders who showed less discrepancy as pulsetakers to be aware of the promising innovative trends of CLT design and construction.

Conclusions

This paper presents the results of a longitudinal analysis of the collaborative networks of CLT projects in the UK. The study depended on the published data of 100 projects in the UK to construct the interorganizational collaborative network between the architects, structural engineers, main contractors, timber contractors, timber engineers and timber manufacturers. Network and nodal SNA metrics were used to analyze the topology and the stakeholder roles of the complete network

and over the analysis time. Seven network metrics were used: average weighted degree, weighted degree variance, centralization, density, modularity and transitivity. Three nodal centrality metrics were used to assess the connectedness degree, betweenness and closeness of the CLT stakeholders.

The study contributes to the field of industrialized and CLT construction by characterizing the collaborative networks between CLT supply chain stakeholders that are critical to propose governmental policies and industry initiatives to advance this sustainable construction material. Governmental policies for reforming and improving the construction industry can benefit from this study by identifying the influence changes of the CLT supply chain stakeholders and the topology patterns of their collaborative networks (Rutten *et al.*, 2009). The study highlighted the scale-free structure of the CLT collaborative network that depends on the influential hubs of timber manufacturers, engineers and contractors to accelerate the innovation diffusion. However, this positive outcome comes at the expense of the vulnerability of the CLT supply chain due to its dependence on these few prominent hubs. Also, the industry collaborative network's decreased modularity confirms the maturity of the CLT technology and the formation of cohesive clusters of innovation partners. The macro analysis approach of the study highlighted the critical role of supply chain upstream stakeholders due to their higher centralities in the collaborative network and knowledge accumulation over their CLT projects. As part of the industry maturity, the CLT foundational knowledge has been disseminated through design manuals and best practices, which strengthened the collaborations between the supply chain upstream stakeholders (timber manufacturers) and downstream stakeholders (architects and main contractors).

The study is limited to the geographical scope of its data sample and it can be expanded in future studies to analyze other geographies and the direct correlation of the collaborative networks with CLT innovations. Despite its sufficient size and data quality, the analyzed sample of the CLT projects is confined to the UK market and did not include projects from other geographies. However, the construction industry is not a globalized industry and each geography is subject to unique jurisdiction, economical, social and environmental conditions. As such, similar future studies can be conducted to critique and validate the observed collaborative network characteristics in other geographies, like North America. Also, future studies can attempt to correlate between the observed collaborative network characteristics and the actual diffusion of CLT material and system innovations. Such studies would require more detailed and localized data collection of a smaller sample or case studies of CLT construction projects.

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