León William. & Guevara, Jose. (2023). Semantic network analysis of lean construction literature. *Proceedings of the 31st Annual Conference of the International Group for Lean Construction (IGLC31)*, 560–571. doi.org/10.24928/2023/0152

SEMANTIC NETWORK ANALYSIS OF LEAN CONSTRUCTION LITERATURE

León William[1] and Guevara Jose[2]

ABSTRACT

Lean Construction is a philosophy grounded in production theory that play a crucial role in promoting efficient, sustainable, and cost-effective practices across the Construction and Engineering Management (CEM) sector. To understand its impact, it is important to analyze the related concepts, synergies, information gaps, potential research paths, and new terms associated with such domain. Therefore, this research paper aims to develop a graphical and quantitative analysis of the LC literature using Semantic Network Analysis (SNA). The analysis builds a large network of interactions between concepts related to the implementation of the LC philosophy in construction projects, offering a novel perspective on reviewing the LC literature. It provides metrics and graphical tools to characterize, quantify, and interpret LC concepts such as Building Information Modelling (BIM), Integrated Project Delivery (IPD), Last Planner System (LPS), and Sustainable Construction, and enables the observation of emerging relationships with opposing concepts such as Earned Value Management (EVM) or information gaps related to Risk Assessment, Decision-Making, or Planning Reliability, which are equally crucial for the implementation of CEM. Overall, this study offers valuable contributions to the IGLC community by providing new perspectives on potential research routes and emerging concepts in the LC literature. It achieves this by synthesizing the relationships between LC ideas and concepts that are not traditionally connected to LC principles, such as Earned Value Management (EVM).

KEYWORDS

Lean construction, construction and engineering management, and semantic network analysis.

INTRODUCTION

Researchers in the field of Construction and Engineering Management (CEM) have developed useful methodological tools by leveraging quantitative and graphical analysis of bibliographic reviews (Herrera et al., 2020). While Lean Construction (LC) has been thoroughly studied over the past decades, there is a notable gap in the CEM domain when it comes to the integration of LC with other essential concepts in the construction industry (Heigermoser et al., 2019). Based on that, this study aims to address this gap by examining the relationships between LC studies and other relevant investigations focused on concepts, such as Building Information Modelling (BIM), Integrated Project Delivery (IPD), Earned Value Management (EVM), and sustainability.

In order to develop a quantitative and graphical synthesis of LC and its connection with other relevant concepts in the CEM domain, the study utilizes Semantic Network Analysis

[1] Ph.D. research assistant, Civil and Environmental Engineering Department, Universidad de los Andes, Bogotá, Colombia, wm.leon10@uniandes.edu.co, https://orcid.org/0000-0002-2533-853X

[2] Associate Professor, Civil and Environmental Engineering Department, INGECO research group director, Universidad de los Andes, Bogotá, Colombia, ja.guevara915@uniandes.edu.co, https://orcid.org/0000-0002-3485-9169

(SNA) (Salazar et al., 2021). This analytical tool allows for the development of networks between associated concepts in a literature review, making it possible to analyze LC and its synergies with other important ideas (Wen & Qiang, 2016). By characterizing, quantifying, and interpreting concepts that are commonly associated with LC and other terms with wide application in the construction sector, this analysis aims to provide a set of metrics and graphical tools that researchers can use to gain a deeper understanding of LC (Castelblanco et al., 2021). Thus, examining the integration of LC and CEM ideas.

POINTS OF DEPARTURE

LEAN CONSTRUCTION

Lean Construction is a philosophy grounded in production theory that play a crucial role in promoting efficient, sustainable, and cost-effective practices across the Construction and Engineering Management (CEM) sector (Koskela et al., 2002). The main focus of this philosophy is on improving the management and administration of construction projects by continuously improving processes, reducing waste, and increasing the final value of the construction product for the customer (Koskela et al., 2002). The adoption of this philosophy leads to higher productivity in processes, which in turn results in increased profitability of projects while minimizing the processes associated with the loss of value of the final product (Aslam et al., 2020). Hence, LC is considered a vital tool for optimizing resources and eliminating waste (Igwe et al., 2020).

SEMANTIC NETWORK ANALYSIS

SNA is a methodological approach for the analysis of dense networks between associated concepts, provides a quantitative, qualitative, and rigorous analysis of the existing synergies between concepts in literature (Motter et al., 2002; Pishdad-Bozorgi et al., 2017). Based on the development of networks of related words, this association analysis enables the extraction of metrics and the production of clear objectives and complex analyses related to the general structure of the relationships (Motter et al., 2002). The structure of this methodology involves creating a network of interconnected nodes from a set of words. If words are not associated with other nodes, this methodology reveals isolated connections or relations of interdependence between them (Herrera et al., 2020; Motter et al., 2002).

Using SNA allows for quantitative analyses of keywords from different articles and provides graphic and mathematical results (Zhai et al., 2014). Moreover, this technique enables the analysis of large databases with low computational requirements, making literature reviews more complex and comprehensive (Han et al., 2018). Therefore, this study employs SNA in evaluating and analyzing the LC and CEM literatures.

CONTENT ANALYSIS

Content analysis (CA) is a valuable technique that complements the SNA methodology. It involves a set of methodologies that allow researchers to extract information from a qualitative or quantitative interpretation of texts (Yearworth & White, 2013). By filtering, categorizing, and classifying information, researchers can carry out objective analyses that are suitable for graphic and mathematical analysis (Elo et al., 2014). In this study, the authors used content analysis to group themes, select fundamental concepts, evaluate trends, establish recurrences, and facilitate the SNA study of LC. In combination with SNA, content analysis enables a comprehensive and in-depth analysis of the literature on LC.

COMMUNITY ANALYSIS

Community analysis is a quantitative strategy used to understand and analyze the behavior of related concepts within a small group compared to the main network being studied (Newman, 2004). This tool helps researchers observe the grouping of sets of nodes that share similar characteristics. Community analysis is highly useful for characterizing underlying communities in large databases (Blondel et al., 2008). It also provides graphical complements that aid in understanding the overall network of nodes (Newman, 2004). By combining SNA, CA, and community analysis, this study analyzed LC and identified associated concepts and main networks from a rigorous selection of 500 research articles from bibliographical resources.

RESEARCH METHODOLOGY

The integration of SNA, CA, and community analysis in this study provides a synthetic view of the key concepts associated with LC. This methodology generates quantitative metrics that reveal significant relationships between LC and other concepts, while graphical representations visually demonstrate the density of these connections. The approach comprises six steps, as presented in Figures 1 and 2, and discussed below.

FIRST STEP – PAPER SELECTION STRATEGY

This stage involved the search for relevant articles on the Web of Science database. From the selected articles, a set of core concepts were extracted to establish the scope of the SNA network and to guide the search patterns used in the Web of Science and Scopus search engines (Doerfel & Barnett, 1999). This search yielded approximately 1,800 records. For the first search cycle only the term Lean Construction was used. After finding a first group of high-recurrence keywords, the search was supplemented with a second cycle that included keywords as Building Information Modelling, Last Planner System, Integrated Project Delivery, and Sustainability.

SECOND STEP – PAPER FILTERING AND CATEGORIZATION

After obtaining an initial total of 1,800 records in the Web of Science database, only the highest quartiles (1, 2) and records related to CEM were selected, resulting in a final set of 500 articles based on citation rates (de Castro e Silva Neto et al., 2016). The objective of this selection was to define the scope of the research and obtain a set of highly relevant articles for the SNA study. Moreover, this set of 500 articles was classified based on their type and central theme to identify research trends and recurrent thematic nuclei in academic research (Castelblanco et al., 2021). This exercise enabled the observation of the most recurrent themes in LC academic research, with the involvement of peer reviewers.

THIRD STEP – KEYWORDS SELECTION

This phase focused on extracting keywords from the 500 research articles (Bao et al., 2018). Titles, abstracts, and introductions of each article were analyzed, along with keywords suggested by the author, journal, and database. The extracted keywords were then filtered based on their significance and recurrence within the article. A maximum of 10 keywords were selected from each article to enhance SNA analysis by concentrating computational efforts on the most relevant and representative words (Eteifa & El-adaway, 2018). A standardization process was carried out to eliminate keyword redundancies, leading to a final set of 975 keywords across all 500 articles. This standardized approach improved the interpretation of the research articles by highlighting their core ideas, communicative intent, and content, and provided greater clarity for the subsequent SNA and CA analyses.

FOURTH STEP – MATRIX DEVELOPMENT

This step involved a quantitative analysis to determine the recurrence ratio of each keyword in the 500 articles. A matrix was constructed with 975 rows and 500 columns, where each row represented a keyword and each column represented an article (Castelblanco et al., 2021). A value of 0 was assigned to the intersection of a keyword and article if the word was absent from the article and 1 if it was present. Subsequently, the transposed matrix was created, with the number of articles in the rows and the total number of keywords in the columns (Hanneman & Riddle, 2005). This matrix allowed for the identification of the recurrence relationship between pairs of words. Finally, the multiplication of the keyword adjacency matrix and its transposed matrix was carried out to complete the process. This methodology enabled the identification of the most important and recurring keywords in the literature related to Lean Construction (LC) and their relationships with other concepts.

Fifth Step – Network Development

A general network was built, and it was possible to observe the geometric configuration of concepts, density of the network, key concepts, and the periphery of the network. This graphical analysis can show isolated or less relevant concepts. A specific network was built for specific subgroups (sub-communities) with high relevance in the main network.

Sixth Step – SNA Metrics and Validation

The collected data was analyzed for coherence and consistency, and validated using UCINET, Gephi, and Microsoft Excel software. It is important to acknowledge that the methodological categorization of keywords can be subjective, leading to limitations in generalizing the state of the art in LC (Bao et al., 2018). However, this article followed a rigorous validation process, including peer review to filter keywords, and verification of connection nodes across different software platforms.

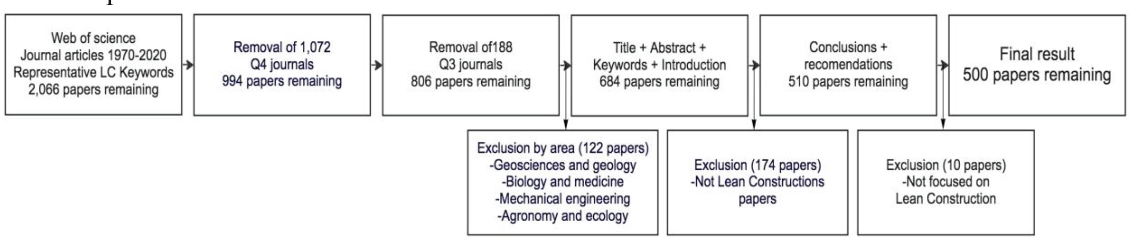

Figure 1: Paper filtering and categorization

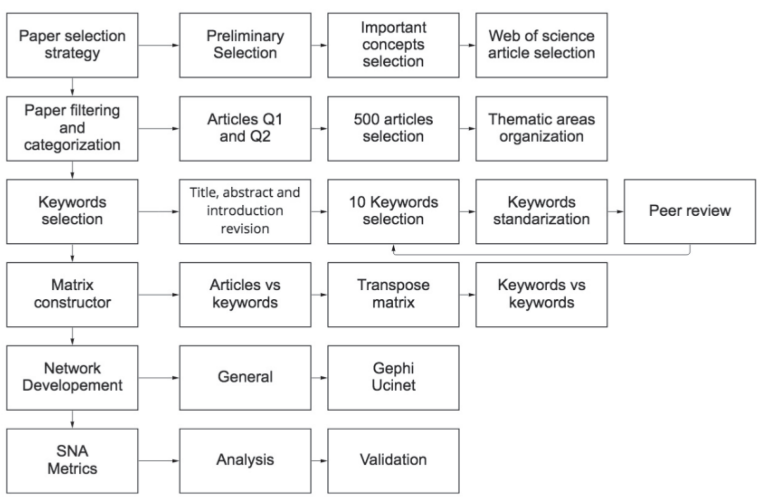

Figure 2: Methodology

RESULTS

The methodology stage yielded a set of networks (1 general structure and 5 sub-structures) that reflect the overall behavior of the LC-related literature and its primary relationships with recurring keywords within the CEM domain. It is noteworthy that the primary outcome is the creation of a semantic network between the 975 filtered keywords and a specific analysis of the sub-communities identified in the modularity coefficient analysis. To fully comprehend the significance of the centrality and cohesion metrics acquired in this study, several concepts have been defined in Table 1, as shown below.

Table 1: SNA Metrics

SNA metric	Meaning
Density	The number of co-occurrences between all keyword pairs as a percentage of the total number of coexistences between all keywords is referred to as density. (Hanneman & Riddle, 2005).
Clustering Coefficient	Metric used to quantify how closely related concepts are to one another. It is higher when particular thematic groups show strong internal interconnection (Freeman et al., 1991).
Modularity	The density of links within communities as opposed to links between communities is measured by a scalar value between -1 and 1, which is known as modularity. (Blondel et al., 2008).
Number of Connections	The quantity of connections between nodes serves as a measure of connectivity and the significance of each individual node inside a network. (Eteifa & El-adaway, 2018).

GENERAL NETWORK

Table 2 summarizes the cohesion metrics found in the semantic network of LC. The general network consists of 975 nodes and is formed by several sub-communities. These communities share common characteristics and are grouped based on color patterns to facilitate separate study. The analysis of communities provides valuable insights to researchers into the interrelationships between different concepts across the field of LC.

The network presented in Figure 3 shows the principal concepts observed in the center of the graph and less important concepts observed in the periphery. A summary of the nodes with the greatest impact is shown in Table 3, along with some of the most relevant centrality measures for this study.

PROJECT MANAGEMENT AND ORGANIZATIONAL CULTURE

The first sub-community identified on the main network is Project Management, as shown in Figure 4. This network comprises a high number of nodes, representing approximately 28.7% of the total network. The next community identified within the main network is Organizational Culture, which is the largest community, accounting for 36.5% of the nodes, as shown in Figure 5. Table 3 group the main nodes, which exhibit high level of density for both structures.

PRODUCTION PROCESS AND MODEL ANALYSIS

Production Process is the smallest community in the whole network. It includes 10 nodes and 17 relationships, comprising around 1% of the main network, as shown in Figure 6. On the other hand, Model Analysis entails roughly 8% of all keywords with 75 nodes and 149 connections. It shows few relationships per node despite exhibiting strong modularity indicators, low density, and high fragmentation as shown in Figure 7.

CONSTRUCTION PROCESS

This community is a medium-sized network with 77 nodes and 139 relationships. Metrics indicate high modularity and low density, with nodes exhibiting few relationships, as compared with other communities. Furthermore, this community also presents a small number of relationships, as shown in Figure 8, but it still represents a sizable portion of the total nodes, comprising about 8% of them.

Table 2: Network-based Measures

		Nodes	Number of Connections	Density	Clustering Coefficient	Modularity
	General Network	975	11852	0.025	0.774	0.226
Sub-Community	Project Management	280	4137	0.106	0.749	0.148
	Organizational Culture	356	1218	0.019	0.742	0.708
	Model Analysis	75	149	0.054	0.901	0.91
	Construction Process	77	139	0.048	0.867	0.931
	Production Process	10	17	0.378	0.75	0.612

Table 3: Node-based Measures

ID	Keyword	Number of Connections	Degree Centrality	Eigenvector Centrality	Betweenness Centrality
General Network					
A454	Lean Construction	1678	0.008	0.302	0.102
A337	Green building	911	0.006	0.296	0.071
A52	BIM	880	0.001	0.015	0.001
A145	Construction Industry	870	0.009	0.179	0.031
A405	IPD	789	0.009	0.245	0.015
Project Management (Sub-Community 1)					
ID	Keyword	Number of Connections	Degree Centrality	Eigenvector Centrality	Betweenness Centrality
A454	Lean Construction	1185	0.599	0.252	0.112
A52	BIM	648	0.473	0.226	0.052
A337	Green Building	636	0.032	0.017	0.001
A145	Construction Industry	621	0.444	0.229	0.033
A405	IPD	563	0.419	0.223	0.025
Organizational Culture (Sub-Community 2)					
ID	Keyword	Number of Connections	Degree Centrality	Eigenvector Centrality	Betweenness Centrality
A966	Workflow	47	0.115	0.559	0.195
A267	Earn Value Method	39	0.085	0.260	0.101
A461	Lean Production	38	0.090	0.490	0.085
A154	Construction Planning	24	0.065	0.296	0.053
A567	Organizational Culture	23	0.068	0.304	0.077
Production Process (Sub-Community 3)					
ID	Keyword	Number of Connections	Degree Centrality	Eigenvector Centrality	Betweenness Centrality
A489	Machine learning	2	0.333	0.458	0.183
A529	Mining industry	2	0.333	0.199	0.211
A933	Variation In Production	2	0.222	0.410	0.067
A951	Waste In Construction	2	0.222	0.381	0.071
A974	Worker Change	2	0.222	0.109	0.066
Model Analysis (Sub-Community 4)					

ID	Keyword	Number of Connections	Degree Centrality	Eigenvector Centrality	Betweenness Centrality
A120	Computation Modelling	4	0.068	0.351	0.141
A548	Multiple Regression Model	4	0.068	0.203	0.239
A870	Task Duration	4	0.068	0.386	0.063
A889	Time Buffer	4	0.068	0.471	0.077
A553	Nonlinear Dynamic Analysis	4	0.068	0.212	0.021
Construction Process (Sub-Community 5)					
ID	Keyword	Number of Connections	Degree Centrality	Eigenvector Centrality	Betweenness Centrality
A170	Construction system	5	0.079	0.782	0.311
A146	Construction innovation	3	0.053	0.010	0.083
A406	Integrated Project Team	3	0.053	0.010	0.105
A471	Line of balance	3	0.053	0.619	0.191
A609	Policymaking	3	0.053	0.001	0.049

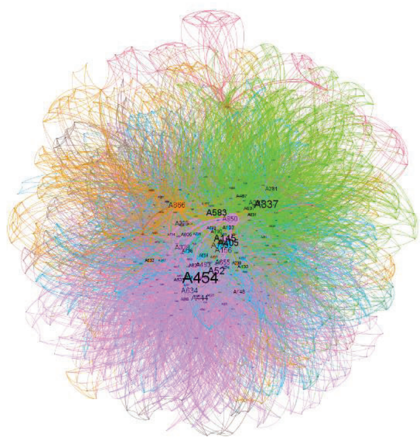

Figure 3: General Network

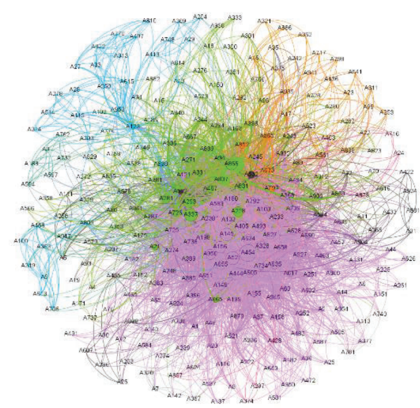

Figure 4: Project Management

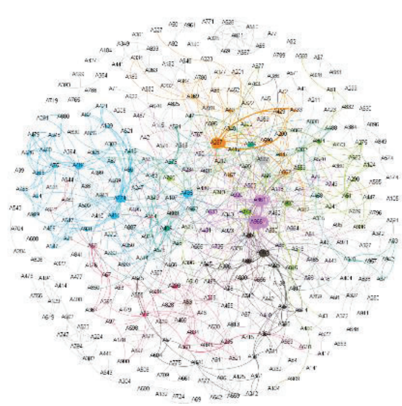

Figure 5: Organizational Culture

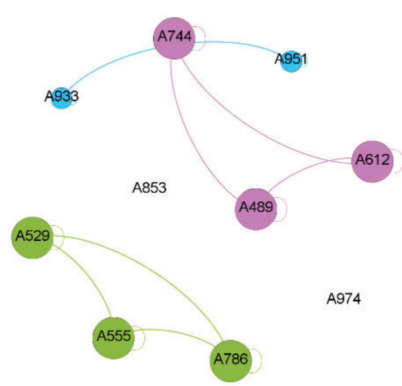

Figure 6: Production Process

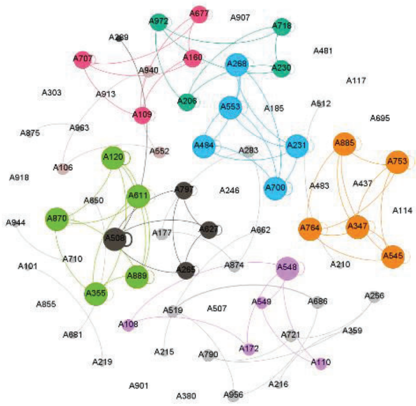

Figure 7: Model Analysis

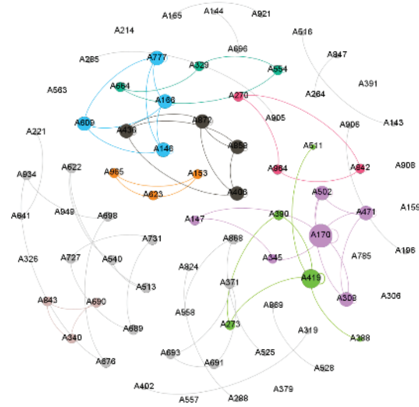

Figure 8: Construction Process

DISCUSSION

The review of literature derived from the SNA model yielded important results regarding the current state of art of Lean Construction (LC). The analysis shed light on concepts of greater proximity, the intensity of the interrelationships, and most importantly, the existing knowledge gaps between LC and some of the most recurring concepts aimed at optimizing and improving processes in the CEM domain.

Firstly, as expected, LC is the term with the highest recurrence in the main network. Concepts such as the Last Planner System (Ballard, 2000), Integrated Project Delivery (Eckblad, 2007), and Building Information Modelling (Sacks et al., 2010) are the closest concepts to LC in current literature, which aligns with Lean principles (Power & Taylor, 2019). In contrast, concepts such as Target Value (Gomez & Rameson, 2019), Flow Value, and choosing by advantages (Schöttle et al., 2019) are concepts that not appear because they are within the principles of LC and are a type of redundance inside the SNA model.

Secondly, the network analysis mathematically confirms the existing relationship between LC, Integrated Project Delivery, Last Planner System, and Building Information Modelling, but it also identifies new terms that are not conventionally associated with LC. Particularly, the emergence of Green Building (Pasquire & Ebbs, 2017; Sarhan et al., 2018) within the five most important nodes around LC is an interesting discovery. While LC is commonly associated with value generation, waste reduction, or continuous improvement (Landim et al., 2022), its association with sustainable development and environmental responsibility concepts is relatively novel. This reveals a new avenue of research that delves into understanding the synergy between LC and the implementation of sustainable projects (Sarhan et al., 2018). Recent construction projects have shown a trend towards coordinated implementation of LC principles and environmental impact mitigation strategies, which is compatible with the findings in this research article (Francis & Thomas, 2019). Furthermore, terms such as Green Building (Ruiz & Guevara, 2021) are shown to be more prominent than terms such as Project Performance, Productivity, or Process Optimization. This highlights the dynamic nature of LC and its ability to adapt to the new requirements and needs of the environment.

Thirdly, while the network analysis confirms the quantitative relationship of LC with traditional and new concepts, it also highlights gaps in literature regarding LC philosophy. Issues such as risk assessment and mitigation (Andenaes et al., 2019) are not extensively documented in relation to LC, and concepts such as Planning reliability or Decision-Making (Abdel-Jaber et al., 2022) are not explicitly linked to LC, but are undoubtedly critical to the structuring and execution of construction projects. Similarly, the lack of connection between LC and quality or innovation indicates gaps in knowledge and presents opportunities for new lines of research aimed at continuing to refine, understand and implement LC. In this way, the proposed SNA methodology enabled the verification of relationships, identification of new synergies, and characterization of knowledge gaps.

In addition, it is important to mention that despite the existing relationship between EVM and LC, EVM has been characterized as not being fully compatible with LC implementation (Kim & Ballard, 2010). However, the relationship between these two concepts exists and is strong due to recurring research that criticizes, compares, and/or combines EVM with LC principles (Cândido et al., 2014). Accordingly, this study not only finds LC linkages with compatible concepts that present synergy and complement each other but also finds terms or concepts that, despite seemingly going against LC postulates, are necessary to explain and deepen the existing knowledge. This also denotes that researchers around the world are examining the possibility of combining EVM with Lean, which is a preliminary indication of how construction projects are being developed worldwide (Cândido et al., 2014).

Finally, the results highlight the importance of variability in the execution of construction projects and their relationship with LC. For example, the process-oriented philosophy of LC, which emphasizes continuous improvement, is closely linked to reducing variability in processes, durations, and methods (Fischer et al., 2021). Therefore, investigating the relationship between LC implementation and variability reduction through performance metrics and indicators could provide valuable insights for future research.

IMPLICATIONS

The current research has practical implications for academics and practitioners in the CEM domain, as the employed methodology improves transparency and highlights semantic connections in a synthetic manner. As demonstrated in Table 3 and Figures 3-8, this study establishes links between LC keywords and critical CEM concepts. This is particularly relevant for those who are not familiar with the LC philosophy.

Results show that Machine Learning has emerged as a powerful tool in LC research (Pasquire & Ebbs, 2017). Technological innovations and computational developments have opened up new avenues for research that complement traditional methods and have provided new opportunities to study and deepen LC principles through modelling or numerical analysis tools. This development suggests that LC is increasingly being analyzed through data-based reasoning, a trend that is likely to gain more popularity in the years to come.

Furthermore, this study highlights the close association between non-linearity and complexity in the context of construction, which is a significant knowledge gap in LC literature (Murguia & Urbina, 2018). This gap indicates the need for future research to explore the complexity of construction projects, their uncertainty, and dynamics in greater detail through emphasizing LC ideas. It is found that LC has a determinant impact on the construction industry, as other economic sectors such as the mining industry have been interested in adopting LC philosophies for the execution of their processes (Castillo et al., 2015).

The analysis also reveals that the term "construction system" is commonly used in LC literature, implying that future research can focus on a systemic view of construction processes (Vásquez-Hernández et al., 2022). This view emphasizes construction as a large system with elements that are interconnected, interdependent, and constantly evolving.

CONCLUSION

The literature review presented in this study provided a visual and quantitative analysis of the linkages between LC and CEM concepts. The study reveals significant knowledge gaps that are linked to the interior of construction projects but are absent in their relationship with LC. These findings have the potential to reveal a new landscape for LC research, with knowledge gaps that are likely to continue existing due to the evolution of LC.

The proposed literature review highlights the significance of LC in the CEM domain and the close synergies it shares with essential concepts such as IPD, LPS, BIM, and Green Building. The SNA offered the authors the opportunity to visualize the nodes associated with LC and the communities underlying this large network. The study reveals approximately 975 keywords grouped in a network with high values of clustering coefficient, density, and modularity.

The fragmentation of nodes in smaller communities with similar characteristics suggests that concepts associated with LC exhibit modular behaviors. This indicates that there are groups of nodes that tend to be more related to specific groups of keywords, making it difficult for a node to connect with other communities. However, terms such as LC, LPS, IPD, and Green Building tend to have low modularity and are often related to more than one community. This implies that most communities have low density values because they are not significantly related to each other.

The also study shows that there are critical gaps in academic research related to LC and concepts such as Risk Assessment, Decision Making, Artificial Intelligence, Planning Reliability, and Innovation in Technology. This finding highlights the importance of utilizing graphical and quantitative tools to identify current relationships, discover new links, and identify information gaps to further advance researchers' understanding and application of LC in the construction industry.

Overall, this study offers valuable contributions to the IGLC community by providing new perspectives on potential research routes and emerging concepts in the LC literature. It achieves this by characterizing the relationships between LC ideas and concepts that are not traditionally connected to LC principles, such as Earned Value Management (EVM).

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