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Research article

Framework for implementing lean construction: from concept knowledge to continuous training

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ABSTRACT

Implementing lean construction (LC) in companies is critical to improving resource management, reducing waste, and enhancing efficiency, leading to increased productivity and reduced costs. However, the absence of structured frameworks and sufficient knowledge in these companies presents significant challenges for effective LC implementation. This study develops and validates a comprehensive framework for managing LC knowledge in companies by examining the relationship between LC principles and three knowledge levels: knowledge of LC concepts, knowledge of LC implementation, and LC continuous training. Based on a thorough review of the current literature and feedback from 23 international LC experts through two Delphi method rounds, the framework comprises 12 variables that integrate LC principles with these knowledge aspects. The framework also emphasizes the importance of top management support and effective communication for successful implementation. Statistical analyses, including the mean, standard deviation, Kendall's *W*, consensus formula, Mann–Whitney test, and Kruskal–Wallis test, were employed to assess the overall level of agreement among LC experts on the framework variables. The resulting framework addresses the existing knowledge gaps and provides construction professionals with actionable insight, setting a clear path for future development of LC practices. This framework allows professionals to improve workflows and reduce inefficiencies while driving continuous company improvement.

1. Introduction

In the dynamic and progressive environment of the construction industry, where construction is planned, designed, and implemented, lean construction (LC) has emerged as a shift from traditional practices to a more sustainable and efficient industry [1]. In addition, LC draws inspiration from the lean manufacturing principles developed by the Toyota Production System [2], focusing on creating value, eliminating waste, and continuously improving processes [3].

Despite scientific evidence demonstrating the advantages of LC, its adoption varies significantly across companies in various regions [4]. Many of these companies face challenges in adopting LC, regardless of the country [5,6]. One of the primary challenges is the limited understanding of its philosophy among industry professionals [7]. Many researchers have found that the most significant barriers influencing the adoption of LC in construction companies are associated with knowledge-related factors [5–9]. In this regard,

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training programs often fail to adequately equip workers and managers with the necessary skills to implement lean practices effectively [6,10]. The construction industry also resists change, with many stakeholders hesitant to abandon traditional practices [5,8]. These challenges impede the widespread adoption of LC, especially in countries in the initial stages of implementation [5,10,11], limiting its potential to enhance efficiency, reduce costs, and promote sustainability [12].

Research on LC has significantly advanced over the past decade, leading to developing numerous tools to facilitate its adoption [5,13–15]. Although expanding LC tools has created more opportunities for constructors, it has also introduced challenges in determining which tools to select and how to initiate their adoption [16]. Companies transitioning to LC must invest considerable time in studying LC knowledge to assess their current position and identify the most suitable tools. A misunderstanding or incorrect selection of LC tools can result in the failure to transform traditional practices [17]. Green (2019) described the LC philosophy as a “complex cocktail of ideas.” This complexity primarily arises from the lack of a sufficient and ongoing structure for improving performance, minimizing waste, and maximizing user value [18].

Researchers have significantly contributed to classifying LC tools in a performance-based framework, leading to diverse implementation scenarios, each considering the unique internal characteristics of companies [5,13,15,19–22]. However, a noticeable gap remains in the ability of these frameworks to guide construction companies in achieving a comprehensive approach to LC knowledge. Guidance in LC knowledge is essential to help companies analyze the specific contextual challenges they face when initiating LC adoption [14], such as: embracing stubbornly traditional methods and resisting change, insufficient understanding of LC concepts and how to implement them, inadequate employee training, continuous improvement initiatives, and finally, inconsistent or unsupportive government policies [4,5].

Therefore, the primary objective of this study is to develop a comprehensive framework for managing LC knowledge. This framework can help companies, from those in the initial stages of LC implementation to those with the highest levels of expertise, to assess their weaknesses and identify the critical elements for increasing LC knowledge to guarantee efficiency in LC implementation. Developing an LC framework benefits construction companies significantly by identifying the best tools to achieve improved results according to industry challenges [15]. This study aims to analyze and validate the relationship between LC principles and LC knowledge levels to achieve this framework, identifying the challenges that influence effective and efficient LC implementation in construction companies.

This study begins by examining the transition of the construction industry to LC, emphasizing the need for further research to develop frameworks facilitating this transition, particularly in countries in the initial stages of LC adoption. Section 2 reviews existing LC frameworks and identifies knowledge gaps. Next, Section 3 proposes a comprehensive LC knowledge (LCK) framework. Then, Section 4 explains the research methods, and Section 5 presents the findings. Further, Section 6 provides a detailed discussion of the comprehensive LCK framework development. Finally, the conclusion summarizes the crucial contributions, highlighting the limitations of the study and offering recommendations for future research.

2. Literature Review

2.1. *Existing lean construction frameworks*

This section reviews the existing LC frameworks, highlighting knowledge gaps regarding their applicability to construction companies. Several scholars have developed frameworks for companies to enhance advanced LC adoption or promote a strong understanding of LC practices. However, the frameworks in the existing literature have focused on (1) specific technical, managerial, and operational aspects connected to LC or (2) analyzing the LC maturity of companies. These frameworks are summarized in this section.

In 2007, Johansen and Walter [23] conducted a survey of 61 companies to determine how well German contractors understood LC principles; however, their research did not offer a framework addressing the specific challenges encountered by these companies. A framework introduced in Brazil combined the principles proposed by Koskela, Womack, and Jones [24] to evaluate various aspects of LC. However, this framework lacked a clear structure, best practices, and a clear definition [14]. Building on this, in a master’s thesis, authors in Brazil [14,25] developed an additional framework assessing the lean maturity of a company, which was also based on the LC concepts by Womack and Jones. These two frameworks were developed exclusively for the Brazilian construction industry and did not include measurement tools or criteria for evaluating LC knowledge. Al Aomar [26] developed a framework that combined technical and human factors to minimize waste and implement lean principles in construction industry scenarios. However, this framework was designed for companies specializing in LC implementation and did not address the problems confronting companies with low or no implementation.

Banawi and Bilec [27] presented a framework prioritizing waste reduction by combining lean, green, and Six Sigma principles, but did not address the critical importance of managing LC knowledge in companies with an inadequate awareness and understanding of LC. Similarly, Nesensohn et al. [28] created a framework that combined Koskela’s LC principles with the Capability Maturity Model Integration (CMMI). Although this framework provided five development stages, the approach was general and more effective in companies based in the United Kingdom or similar countries with similar cultures. Carvalho and Scheer [29] developed a framework to study LC in Brazil using a supply chain perspective and the Koskela LC principle, but the framework had no thorough evaluation component and did not offer a practical guideline for companies.

Later, Sainath et al. [30] proposed a multidimensional matrix for assessing LC maturity using data from the International Group for Lean Construction. This framework was primarily based on empirical evidence rather than clear theoretical foundations and was only effective in companies with advanced LC practices. Another framework from the Kingdom of Saudi Arabia [12] used a survey to identify crucial success factors for LC. This framework narrowly focused on the Saudi context and did not sufficiently link the crucial success factors to broader LC principles. Li et al. [31] defined crucial success factors for LC but limited their research to only two companies with a strong understanding of LC, hindering the broader applicability of the framework. Tezel et al. [32] investigated the LC status on highway projects, but the study lacked strength regarding the LC framework and focused on improving the current LC condition for small and medium-sized enterprises. Bajjou et al. [33] proposed a framework for successfully spreading LC by analyzing six relevant frameworks and testing them in several countries, including the United States, the United Kingdom, Malaysia, and Brazil. This framework was only appropriate for companies with a fully developed LC or those with a comprehensive understanding of LC.

More recent frameworks [34,35] have begun to investigate integrating building information modeling (BIM) with LC and lean thinking principles; however, these frameworks are ineffective because they do not address all LC concepts or directly measure maturity. In contrast, a framework presented in Sri Lanka [36] combined a learning-to-learn sand cone model with lean learning in the construction industry. This framework was limited to companies in Sri Lanka and similar neighboring countries and did not employ

Table 1
Existing LC framework approaches, contributions and limitations.

Reference	Approach	Contributions	Limitations
[23]	It applies a survey to German construction companies by using a structured questionnaire.	It offers insights into the awareness and implementation of LC practices among major companies.	It overlooks small and medium companies, and it lacks clear step-by-step guidance or a maturity assessment.
[24]	It presents a questionnaire evaluated by external participants through structure interviews.	It includes Koskela's and Womack & Jones' LC principles, emphasizing waste reduction, value enhancement and process simplicity.	It lacks clear implementation guidelines and best practices.
[25]	It assesses 16 LC practices using a Likert scale.	It includes Koskela's and Womack & Jones' LC principles, addressing waste reduction, standardization, organizational culture, customer focus and continuous improvement.	It does not provide benchmarks nor a measurement scale, being only applicable in Brazil.
[26]	It combines Lean and Six Sigma with cyclical look-ahead planning, using five key performance indicators: quality, speed, cost, value and waste.	It identifies 27 types of waste, focusing on continuous improvement by regularly reviewing and updating the performance indicators.	It is prepared for companies that specialize in LC implementation, and it does not address the challenges faced by companies with minimal or no implementation.
[27]	It integrates the principles of Lean, Green and Six Sigma to enhance the efficiency of construction processes.	It provides a comprehensive approach to the identification, quantification and mitigation of process waste and its environmental consequences.	It develops a single case study, limiting the generalization of results.
[28]	It is based on Koskela's LC principles, using an external advisor to evaluate performance by conducting site visits and staff interviews.	It defines maturity levels, evaluating construction performance.	It is developed for the UK construction context, making it only suitable for similar scenarios.
[29]	It is based on supply chain and Koskela's LC principles using stakeholder surveys.	It is a useful diagnostic tool, checked by 35 case studies conducted in Brazil.	It lacks an evaluation component and does not provide practical guidance for companies, being limited to Brazil.
[30]	It proposes a multidimensional matrix for assessing LC maturity using data from the International Group for Lean Construction.	It provides a structured, quantitative way for assessing LC maturity.	It is based on empirical evidence rather than clear theoretical foundations, being only effective in companies with advanced LC practices.
[31]	It conducts a comparative case study to evaluate the application of LC in two Chinese construction companies using qualitative techniques.	It develops a detailed evaluation index system for LC, identifying factors such as comprehension, organizational culture and market pressure.	Its findings are limited to two case studies conducted in China, and the evaluation framework presumes a solid understanding of lean principles.
[12]	It uses a survey to structure and prioritize 12 CSF for LC implementation tailored to the Saudi construction industry.	It develops a context-specific, hierarchical framework that guides step-by-step lean implementation based on interrelated CSF.	It is restricted to 12 CSFs without linking them to the broader LC principles and focusing only on Saudi Arabia.
[32]	It uses a mixed-methods analysis in order to explore motivations, implementation and barriers to LC in the UK highways sector.	It identifies client pressure and competitive advantage as key motivators.	Its findings are specific to the UK highways sector.
[33]	It creates a conceptual input-output model of LC by critically analyzing six international LC frameworks and synthesizing 33 sub-principles into nine main principles.	It comprises a detailed, organized guide for implementing LC based on widely accepted principles	It is only appropriate for companies with a comprehensive understanding of LC.
[34]	It performs an extensive literature review of maturity models to create an integrated BIM and Lean Maturity Model.	It evaluates the integrated application of BIM and LC practices.	It is theoretical and it has not been empirically validated through real-world application.
[35]	It performs a comparative analysis of 10 well-known BIM maturity models against LC and Integrated Project Delivery.	It identifies which BIM models best align with LC and IPD principles.	It is theoretical, without any real-world testing or empirical validation to support its practical use.
[36]	It integrates the "learning-to-learn sand cone model" through qualitative research.	It proposes a clear six-step lean learning model that includes 52 specific activities.	It is focused on large-scale contracting firms in Sri Lanka, which limits the generalizations of results.
[5]	It employs a quantitative methodology based on a questionnaire distributed to Jordanian building professionals.	It develops a theoretical, pyramidal knowledge-based framework that organizes LC barriers into three levels: conceptual knowledge, implementation, and training.	It is focused solely on Jordan's building sub-sector, excluded specific LC tools, and relied entirely on survey-based data without empirical field validation.

any LC principles, instead focusing on lean learning in construction. Moreover, Hyarat et al. [5] presented a comprehensive knowledge framework that demonstrated how knowledge-related barriers are linked to other barriers that hinder LC adoption in the subsector building industry in Jordan. This framework was limited because it did not link directly to LC principles and was more suitable for the subsector building industry in Jordan.

The following Table 1 summarizes the previously discussed existing LC frameworks, by order of appearance in the text. This comparison helps identify the knowledge gap and the significance of the suggested approach.

2.2. Knowledge gap

Knowledge-related factors determine the effective, efficient implementation of LC. Existing LC frameworks focus on enhancing LC implementation and guiding companies in selecting best practices. Most existing frameworks were designed for companies with advanced LC practices, where the industry is more familiar with LC principles, tools, and techniques, or were designed for construction companies in specific countries. However, companies in the initial stages of LC adoption encounter unique challenges, including limited knowledge sharing, a lack of understanding of LC principles, and insufficient alignment of these principles with local construction practices.

This gap underscores the necessity of a more comprehensive framework that facilitates LC adoption. The framework should focus on managing and sharing LC knowledge, training construction professionals, and aligning LC principles with the specific needs of companies implementing LC. By building on the work of Hyarat et al. [5], who classified LC knowledge into three distinct stages that offer a comprehensive foundation for understanding and organizing LC knowledge, this study proposes a detailed and scalable framework for managing LC knowledge in construction companies. This framework overcomes the challenges associated with limited knowledge and the misalignment of LC principles, enabling more successful and sustainable LC practices in these contexts.

2.3. LC knowledge framework Proposal

The primary study objective is to develop a comprehensive framework for managing LC knowledge in companies regardless of their level of expertise in this field. The LC principles and critical elements related to its adoption—specifically the knowledge aspects of conceptual understanding, practical implementation, and continuous training—have often been examined in isolation in the literature. Integrating these two perspectives offers a more cohesive approach, significantly enhancing LC adoption across companies. This framework emerges from a comprehensive analysis of the critical challenges influencing LC adoption, LC principles, and the existing knowledge gaps while synthesizing insight from multiple studies on LC practices. The proposed LCK framework is structured as a two-dimensional matrix, as illustrated in Fig. 1.

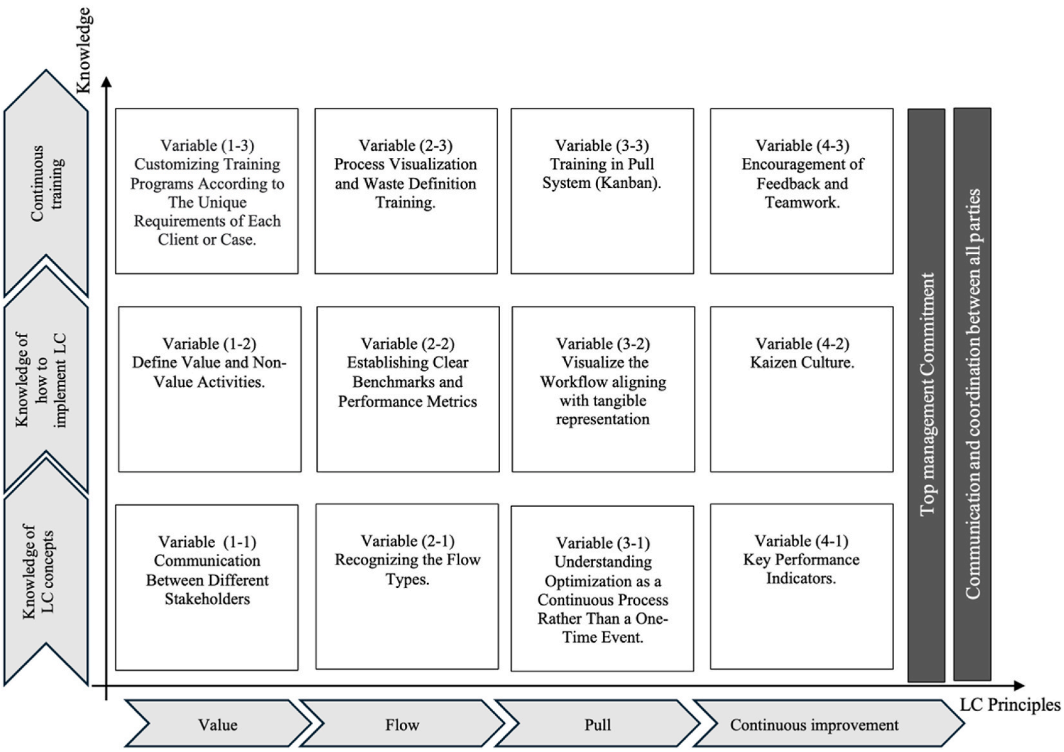

Fig. 1. Lean construction knowledge framework (after pilot study improvement).

As defined by Womack and Jones [37], the principles of lean thinking form an essential framework dimension aligned along the *x*-axis, which includes value, flow, pull, and continuous improvement. For practical purposes, due to the overlap in several aspects of the LC adoption process, value also includes the value stream. This integrated approach ensures that the foundational elements of lean thinking are fully integrated into the framework design. A comprehensive understanding of these principles enables companies to optimize value and minimize waste in construction projects, as articulated by Koskela [38] in an adaptation of lean guidelines for the construction industry. Value, flow, and pull principles are pivotal for achieving efficiency by eliminating activities without value and establishing a demand-driven production system [37–39]. Continuous improvement ensures the sustainability of the system by fostering ongoing refinement across these phases [37].

The second framework dimension (*y*-axis) relates to LC knowledge. This dimension comprises three critical knowledge components identified by Hyarat et al. [5]. These principles serve as the groundwork for LC adoption, particularly for companies adopting LC or enhancing its implementation [5]. The first component, knowledge of LC concepts, focuses on understanding foundational principles, such as waste reduction, efficiency, and productivity [40]. The second component, knowledge of how to implement LC, pertains to the practical application of LC principles to enhance productivity and mitigate inefficiencies in construction projects [41,42]. The third component, continuous LC training, emphasizes the critical role of ongoing education in cultivating and sustaining a lean culture throughout the organization [43]. Structured training programs enable employees to understand and implement LC principles, gradually reducing resistance and fostering a culture of continuous improvement [19].

In the context of LC concepts, communication between different stakeholders (Variable 1-1) is vital for defining value from the customer perspective, helping project teams distinguish between activities that add value and those that do not [44]. Recognizing the flow types (Variable 2-1) is another fundamental aspect of understanding the flow LC principle, enabling teams to align operations and processes to minimize waste and maximize value [45]. The optimization concept in the pull principle, understanding optimization as a continuous process rather than a one-time event (Variable 3-1), requires a continuous approach, where project demands are met by efficiently adapting resources and workflows to ongoing changes [44]. Key performance indicators (KPIs) (Variable 4-1) provide critical metrics to measure lean practice effectiveness, ensuring organizations can continuously improve and meet LC goals [46].

The second row of the framework emphasizes how companies can practically gain knowledge to implement LC. In the value LC principle, defining value and non-value activities (Variable 1–2) serves to identify activities that add or do not add value throughout the construction process after proper communication with the customer. This approach is essential for waste reduction and increased customer satisfaction [47]. Regarding flow, establishing clear benchmarks and performance metrics (Variable 2-2) ensures that the project stays on track and that all team members adhere to standardized processes, minimizing variability and ensuring reliable results [44,48]. Regarding the pull principle, visualizing the workflow aligning with tangible representation (Variable 3-2) is crucial, enabling teams to better understand how tasks align with project demands. This workflow representation ensures that teams know what must be accomplished and when, enhancing the efficient implementation of lean principles [49]. Last, Kaizen culture (Variable 4-2) encourages regular feedback loops, helping teams continuously learn from successes and failures to refine processes [50].

Continuous training is the third component of the LC knowledge aspects in the framework, which is crucial for sustaining LC practices over time. Under the value principle, customized training programs according to the unique requirements of each client or case (Variable 1–3) ensure that team members are equipped to meet the specific needs of each project or client, facilitating the

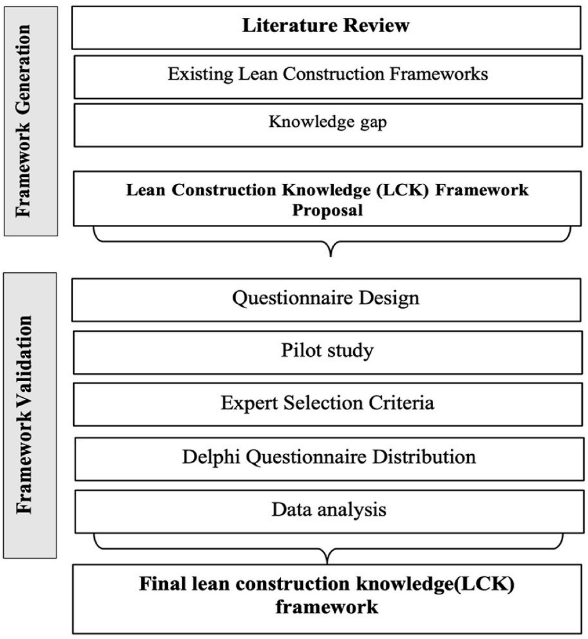

Fig. 2. Research method.

continuous delivery of value [44]. Regarding the flow principle, process visualization and waste definition training (Variable 2–3) help employees recognize and eliminate waste throughout the project life cycle [17,19,47]. Regarding the pull principle, training in pull systems (kanban) (Variable 3-3) ensures that teams are proficient in demand-driven workflows, reducing overproduction and ensuring a smooth and efficient process flow [43,51,52]. Finally, regarding continuous improvement, the encouragement of feedback and teamwork (Variable 4-3) emphasizes training programs that promote collaboration and create an environment where teams are encouraged to share insight, enabling a culture of sustained improvement [36,44].

Furthermore, top management commitment, and communication and coordination between all parties are critical external variables that enhance the effectiveness of the entire framework. Top management commitment delivers the necessary resources, authority, and strategic direction [19], whereas effective communication and coordination facilitate seamless information flow and stakeholder collaboration [43]. By promoting a supportive environment, these variables enhance the overall efficiency of the framework inputs, leading to improved outcomes [52]. Additionally, these variables help align organizational goals, reduce potential conflicts, and promote a shared understanding of the objectives across all levels of the organization, contributing to the success of the framework.

This framework functions as an interconnected matrix, with certain elements critical across multiple stages of the LC principle. For instance, communication is essential in all phases but is particularly critical in the initial phase because it represents the foundation for understanding value. The interconnected and essential nature of these variables is critical because their influence extends beyond a single stage, influencing the overall coherence and effectiveness of the framework. The proposed framework is validated as described in the research method in the following section to ensure effective LC adoption.

3. Research method

3.1. Overall process

Fig. 2 outlines the primary steps in the research method designed to achieve the study objectives. The process starts with generating the framework, as discussed in the previous section, followed by validating the framework using the Delphi technique. This technique is widely employed in the construction research field, helping to gather information and viewpoints from experts to solve a problem [53]. This method was selected for its ability to systematically reach consensus among experts on complex, interdisciplinary issues, such as integrating knowledge with (LC) principles. It is particularly effective in situations where empirical data is scarce and expert opinions are crucial [54,55]. Originally, the Delphi method was used in construction management research to develop frameworks and assess conceptual models [54,55]. Numerous studies on construction safety and innovation have also effectively employed the Delphi method [56,57]. This approach proves especially beneficial when expert insights are necessary to refine factors and ensure their applicability in real-world scenarios [58].

The Delphi technique is an iterative process with steady feedback after completing each round, followed by a statistical analysis of the group responses. The primary objective of this method is to collect answers that achieve a consensus. The anonymity of the responses allows the participants to provide answers without concern for peer judgment. Typically, Delphi studies reach a consensus after two or three rounds [59].

3.2. Questionnaire design

The Delphi questionnaire was divided into two sections to ensure that the logistic aspects and substantive feedback regarding the proposed framework were accurately addressed; the complete questionnaire is attached in Supplementary Materials. The first section requested confirmation from the experts regarding their willingness to participate in the study (as attached in Supplementary Materials), followed by questions about their general demographics (e.g., name, email, years of experience, and work field). This information was crucial for contextualizing the responses and assessing the variety and credibility of the expert panel.

The second section provided a brief description of the proposed framework and its components. Once the experts were familiar with the framework, the questionnaire included questions based on the 12 variables linking the LC principles and knowledge aspects and the two external variables that enhance the overall framework efficiency. These questions gathered information to validate the framework and its variables. A 6-point Likert scale (6: strongly agree, 5: agree, 4: somewhat agree, 3: somewhat disagree, 2: disagree, and 1: strongly disagree) was applied to determine the expert opinions on each question regarding these variables. The Likert scale is widely used to assess attitudes, opinions, or perceptions in surveys and questionnaires [60]. Each question also included an open section to allow experts to provide further suggestions.

3.3. Pilot study

Before initiating the Delphi technique, a pilot study was conducted with a small group of experts in LC. The objective of the pilot study was to evaluate the effectiveness of the distribution method and the clarity, relevance, and structure of the questionnaire [53]. Feedback from the pilot study was employed to modify the questions and improve the overall study design, ensuring successful subsequent rounds and accurate and valid data. Fig. 1 presents the framework after the pilot study.

Four experts participated in the pilot study: two from the academic field with a major in construction management and LC and two who were either familiar with or working with LC tools in the industry. The experts verified the appropriateness and composition of the Delphi questionnaire. They also revised the cover letter, corrected grammatical errors, and adjusted questions to align better with the variables in the framework. With these adjustments, the study proceeded to the next step: selecting LC experts for the Delphi rounds.

3.4. Selection of the expert panel

There is no consensus on the minimum number of experts required to participate in the Delphi technique [61]. However, a review of 88 studies found that the minimum number should be eight experts [58]. Further study on the Delphi method revealed that a panel size of fewer than 25 experts is generally appropriate for construction engineering and management research [54]. The research team sent invitations to 56 experts via email and LinkedIn. These experts were required to meet three criteria [1]: an advanced degree in construction management [2], a minimum of 10 years of professional experience in construction management, and [3] affiliation with an international LC organization. In addition, the experts were categorized into three profiles.

A. **Academic**: University instructors or researchers who teach construction management courses and have published research on LC topics.
B. **Professional Trainer/Coach**: Experts involved in LC-related training programs and coaching activities.
C. **Professional Practitioner**: Practitioners actively using LC tools and techniques in their work.

In total, 23 LC experts participated in the study, with a 41 % response rate. Table 2 lists the exact distribution of the LC experts by profile, experience, and country.

3.5. Delphi questionnaire distribution

The Delphi method used in this study involved a two-round process conducted between March and July in 2024. In the first round, 56 invitations were distributed, and 27 experts participated. These experts were provided a structured questionnaire to capture their opinions on the 12 variables and two external variables that enhance the overall efficiency of the framework. This structured approach ensured that specific relevant feedback could be gathered to achieve consensus on the proposed LCK framework. By the second round, 23 experts participated. Thus, feedback and responses from the four original participants who did not continue to the second round were excluded during data analysis to ensure accuracy and maintain consistency in the expert panel evaluations.

3.6. Data analysis

A comprehensive quantitative analysis was conducted after each round to evaluate the level of agreement and consensus among the experts. This analysis involved calculating the mean, standard deviation, Kendall's W, and consensus formula. Nonparametric tests, such as the Kruskal–Wallis and Mann–Whitney tests, were employed. These analyses provided valuable insight, informing modifications for the next rounds.

Table 2
Specific profile of lean construction experts participating in the Delphi study.

Participants	Years of experience	Profile	Country
Expert 1	30	B	Italy
Expert 2	24	A	Nigeria
Expert 3	10	A	Mexico
Expert 4	30	A	China
Expert 5	30	B	Ireland
Expert 6	11	A, C	Egypt
Expert 7	10	C	Canada
Expert 8	18	A, B	United States of America
Expert 9	23	A	Egypt
Expert 10	32	A, B	United States of America
Expert 11	14	B	Qatar
Expert 12	16	C	Canada
Expert 13	20	A	Canada
Expert 14	40	A	Chile
Expert 15	35	A	Jordan
Expert 16	10	A	United Kingdom
Expert 17	30	A, B	United States of America
Expert 18	19	C	United States of America
Expert 19	25	A	Chile
Expert 20	30	C	Portugal
Expert 21	14	A, C	France
Expert 22	10	A	United Arab Emirates
Expert 23	13	A	Chile

A: Academic, **B**: Professional Trainer/Coach, **C**: Professional Practitioner.

3.6.1. Normality and reliability tests

Normality tests are necessary in many contexts because they evaluate whether the data conform to a normal distribution, informing later analyses, particularly in this Delphi study. Normality tests are essential because they determine whether the following analysis should be parametric or nonparametric [62]. The Shapiro–Wilk test was implemented to evaluate the normality of the data. Data are considered to follow a normal distribution when the *p*-value of the test is greater than 0.05 [62].

After determining the normality of the data, a reliability test assesses how consistently and dependably a measurement instrument or method performs over time. Reliability tests are often employed in research, evaluation, and quality control to ensure that data are collected and analyzed accurately and consistently. These tests are crucial across diverse fields, such as psychology, education, medicine, engineering, and the social sciences. The choice of reliability test depends on the nature of the measurement instrument, the type of data, and the specific research or evaluation design [63]. Cronbach's alpha is a widely used measure for assessing the reliability and internal consistency of a test or instrument. Cronbach's alpha is scored on a scale from 0 to 1, with values equal to or greater than 0.90 considered highly reliable. Values between 0.80 and 0.89 are considered reliable, whereas values between 0.70 and 0.79 are considered moderately reliable. Scores between 0.60 and 0.69 are considered minimally reliable, and values below 0.60 are considered unacceptably unreliable [64]. Cronbach's alpha values were calculated using SPSS software (v.29).

3.6.2. Determination of Delphi rounds based on consensus

Determining the number of rounds for the Delphi process and when it should stop is essential. The level of consensus among experts determines the number of rounds based on statistical data analysis methods. However, the criteria for measuring consensus differ across studies, each employing its own criteria [65]. Von der Gracht (2012) explored assessment techniques for consensus levels using mean values and percentages of agreements [66]. Consensus is reached when the mean value falls within an interval [mean $\pm$ 0.5]. For example, in a scenario where the mean value of all variables is 4.5, the interval would range from 4.0 to 5.0. If most variables fall in this interval, consensus is achieved, and another round is unnecessary [66]. Another method to assess consensus and measure the number of Delphi rounds is through the percentage of agreement. Consensus is achieved if 80 % of the respondents agree on the top measures, such as the three highest response categories, on a 6-point Likert scale [67].

3.6.3. Kendall's W and consensus formula

Kendall's *W* (also known as Kendall's coefficient of concordance) is a nonparametric statistical measure to determine the degree of agreement among participants. Kendall's *W* plays a crucial role in assessing the degree of agreement achieved at each step of the Delphi method, involving multiple rounds of surveys with a panel of experts [68]. However, the consensus formula proposed by Tastle and Wierman (2007), presented in Eq. (1), is also applied [69] to obtain more robust results regarding the degree of agreement among participants and the validation of expert opinions. This formula is helpful for Delphi studies because it measures the importance level by assessing the deviation of responses from the mean or median and how close they are to the center of the group ratings [66,69].

$$C_{ns} = 1 + \sum_{i=1}^{n} P_i \ \log_2 \left(1 - \frac{|X_i - \mu_x|}{d_x}\right), \tag{1}$$

where C_{ns} denotes the overall measure of consensus for an item or set of responses, P_i represents the proportion of total responses within a specific rating or category *i*, X_i indicates the rating or score given by the expert for the item in question, μ_x represents the central tendency of all responses (typically the mean or median), and d_x denotes the maximum possible deviation from the mean or median in the given scale.

A higher C_{ns} value indicates a stronger importance and agreement among experts. Lower values suggest either less importance or more disagreement. This formula validates the expert opinions in Delphi studies by examining how the responses are distributed around the central value. Increasing C_{ns} values validate that the experts are converging toward stable, informed agreement. The C_{ns} threshold values are defined as follows: above 0.80 indicates strong agreement and importance, 0.70 to 0.79 indicates moderate agreement and importance, 0.50 to 0.96 indicates low agreement and importance, and 0.00 to 0.49 indicates null agreement and importance [70].

3.6.4. Kruskal–Wallis and Mann–Whitney tests

Kruskal–Wallis and Mann–Whitney tests were conducted to assess differences in opinion among experts with varying work and experience. These nonparametric tests effectively evaluate group differences. The Kruskal–Wallis test determines whether statistically significant differences exist among three or more independent groups regarding a particular variable. The Kruskal–Wallis test is an extension of the Mann–Whitney test, designed to compare differences between two independent groups. Both tests assess whether significant differences exist between the median values of these groups [71].

Table 3
Cronbach's alpha values for Delphi rounds 1 and 2.

Delphi rounds	*N* of items	Cronbach's alpha
Round 1	14	0.800
Round 2	14	0.871

4. Results

4.1. Normality and reliability tests

The results from the Shapiro–Wilk test demonstrated that the *p*-values for all variables in both rounds were below 0.05, confirming that the data did not follow a normal distribution. Consequently, nonparametric tests were applied for the data analysis. Table 3 reveals that Cronbach's alpha coefficients were 0.800 in the initial round and increased to 0.871 in the following round, indicating that the panelists' responses were consistently reliable for further research. These results offer an initial reference for the descriptive statistical analysis of the Delphi study.

4.2. Determination of the Delphi round based on consensus

The decision to restrict the Delphi method to two rounds was primarily based on the solid consensus (agreement) reached in the initial round, which further increased in the second round, as indicated by the overall percentage of agreement and mean values. Table 4 presents the percentage of agreement analysis. In both rounds, the experts agreed on all defined variables in the proposed LCK framework, with an 80 % or higher agreement rate across the three highest response categories. This result indicates that consensus was achieved after Round 1 and was strengthened in Round 2.

In addition, the mean and median values from Round 1 indicated that experts either agreed or strongly agreed with the defined variables in the proposed LCK framework. The overall agreement was measured based on the mean value falling within the following specific intervals: strongly disagree from 1.00 to 1.82, disagree from 1.83 to 2.65, somewhat disagree from 2.66 to 3.48, somewhat agree from 3.49 to 4.31, agree from 4.32 to 5.14, and strongly agree from 5.15 to 6.00 [72].

In Table 5, in Round 2, the mean values increased, and all experts strongly agreed with all defined variables in the proposed LCK framework, except for developing KPIs combining causal analysis (Variable 4-1), where opinions remained unchanged. This finding indicates that consensus levels were achieved due to the stability of the experts' responses across the rounds. Furthermore, the consensus intervals for this study were set between 3.89 and 4.89 for Round 1 and between 4.50 and 5.50 for Round 2, indicating that all mean values fell within or above these intervals in both rounds.

4.3. Agreement among respondents and validation of expert opinions

The results in Table 6 reveal that Kendall's W value was 0.137 in the first round and 0.142 in the second round. Although both values are below 0.20, they reflect a positive trend toward agreement among the 23 LC experts, indicating that their opinions aligned more closely. Notably, Kendall's W is significantly influenced by the number of experts participating in the study. The diversity of opinions and perspectives can make it more challenging to achieve high agreement levels when working with a larger group. Therefore, even small increases from Round 1 to 2 are significant. Furthermore, it has been highlighted that achieving high W scores becomes more difficult as the number of raters increases; therefore, even relatively low W values can still indicate meaningful

Table 4
Percentage of each response category in Rounds 1 and 2.

Variables (definitions after Round 2)	Round 1				Round 2			
	SA %	A %	SMA %	Sum%	SA %	A %	SMA %	Sum%
Effective communication among diverse stakeholders to clarify their demands along the value chain	47.83	34.78	13.04	95.65	52.17	39.13	4.35	95.65
Define value and nonvalue activities in the context of the project or organization	47.83	34.78	0.00	82.61	65.22	26.09	8.70	100.00
Customizing practical and short-term training to the specific context of each client or case	43.48	30.43	17.39	91.30	52.17	39.13	8.70	100.00
Understanding actual variability and how information, materials, labor, and equipment "flow"	47.83	17.39	21.74	86.96	47.83	43.48	4.35	95.65
Establishing clear benchmarks and performance metrics considering a different perspective	34.78	30.43	17.39	82.61	52.17	17.39	26.09	95.65
Process visualization and waste definition training	56.52	26.09	4.35	86.96	52.17	34.78	13.04	100.00
Knowing the differences between push and pull and understanding optimization as a continuous process rather than a one-time event	39.13	39.13	17.39	95.65	60.87	17.39	17.39	95.65
Visualize the workflow aligning with tangible representation	43.48	43.48	8.70	95.65	52.17	34.78	8.70	95.65
Training on the pull system (Kanban) as one of many aspects of continuous improvement	47.83	34.78	8.70	91.30	52.17	30.43	17.39	100.00
Develop KPIs combining causal analysis	21.74	39.13	26.09	86.96	34.78	30.43	30.43	95.65
Depend on Kaizen culture (feedback loop and learning from mistakes and successes)	56.52	26.09	17.39	100.00	52.17	34.78	13.04	100.00
Psychological safety to guarantee that feedback and teamwork are effective	60.87	34.78	4.35	100.00	69.57	26.09	4.35	100.00
Top management commitment	78.26	21.74	0.00	100.00	82.61	17.39	0.00	100.00
Communication and coordination between all parties	65.22	34.78	0.00	100.00	86.96	13.04	0.00	100.00

SA: strongly agree, **A:** agree, **SMA:** somewhat agree, **KPIs:** key performance indicators.

Table 5
Descriptive analysis: mean and standard deviation.

Variables (definitions after Round 2)	Round 1			Round 2		
	Median	Mean	SD	Median	Mean	SD
Effective communication among diverse stakeholders to clarify their demands along the value chain	**5.00**	**5.22**	**0.998**	**6.00**	**5.35**	**0.935**
Define value and nonvalue activities within the context of the project or organization	5.00	5.04	1.296	**6.00**	**5.57**	**0.662**
Customizing practical and short-term training to the specific context of each client or case	5.00	5.09	0.996	**6.00**	**5.43**	**0.662**
Understanding actual variability and how information, materials, labor, and equipment "flow"	5.00	4.91	1.345	**5.00**	**5.35**	**0.775**
Establishing clear benchmarks and performance metrics considering a different perspective	5.00	4.70	1.396	**6.00**	**5.17**	**0.984**
Process visualization and waste definition training	6.00	5.13	1.392	**6.00**	**5.39**	**0.722**
Knowing the differences between push and pull and understanding optimization as a continuous process rather than a one-time event	5.00	4.96	1.186	**6.00**	**5.35**	**1.027**
Visualize the workflow aligning with tangible representation	**5.00**	**5.26**	**0.810**	**6.00**	**5.35**	**0.832**
Training on the pull system (Kanban) as one of many aspects of continuous improvement	5.00	5.17	1.072	**6.00**	**5.39**	**0.783**
Develop KPIs combining causal analysis	5.00	4.70	0.974	5.00	4.96	0.928
Depend on Kaizen culture (feedback loop and learning from mistakes and successes)	**6.00**	**5.39**	**0.783**	**6.00**	**5.39**	**0.722**
Psychological safety to guarantee that feedback and teamwork are effective	**6.00**	**5.57**	**0.590**	**6.00**	**5.65**	**0.573**
Top management commitment	**6.00**	**5.56**	**1.050**	**6.00**	**5.88**	**0.337**
Communication and coordination between all parties	**6.00**	**5.52**	**1.014**	**6.00**	**5.88**	**0.337**

Note: Variables in bold mark strongly agree; **KPIs:** key performance indicators.

Table 6
Kendall's coefficient of concordance.

Kendall's *W*[a]	0.137	0.142
Chi-square	40.872	42.551
df	13	13
Asymptotic significance	<0.001	<0.001

[a] Kendall's coefficient of concordance.

agreement [73]. Moreover, some studies have suggested that even small *W* values can be significant for panels of more than 10 experts [68].

In contrast, the results of the consensus formula, as shown in Table 7, indicate that both Delphi rounds demonstrated improvement in agreement and notable scores. Most variables exhibited increased agreement from Round 1 to 2, underscoring the successful validation and alignment of the expert perspectives. Several variables shifted from low or moderate to strong agreement, moving toward greater consensus. The high initial values, which remained stable or improved, suggest that the variables were well-agreed upon and thoroughly validated.

4.4. Agreement of the respondents between the expert groups

The Kruskal–Wallis test was applied to examine whether significant differences exist among the responses from academics, industry professionals, and individuals employed in academic and industrial settings, as presented in Table 8. The *p*-value for all variables was greater than 0.05, indicating no significant difference of opinion between the three groups. These findings confirm that the variables

Table 7
Consensus level C_{ns} for all lean construction knowledge framework variables.

Variables (definitions after Round 2)	Round 1		Round 2	
	Consensus	Agreement	Consensus	Agreement
Effective communication among diverse stakeholders to clarify their demands along the value chain	0.74	Moderate	0.76	Moderate
Define value and nonvalue activities within the context of the project or organization	0.66	Low	**0.82**	**Strong**
Customizing practical and short-term training to the specific context of each client or case	0.74	Moderate	**0.82**	**Strong**
Understanding actual variability and how information, materials, labor, and equipment "flow"	0.61	Low	**0.80**	**Strong**
Establishing clear benchmarks and performance metrics considering a different perspective	0.60	Low	0.72	Moderate
Process visualization and waste definition training	0.61	Low	**0.80**	**Strong**
Knowing the differences between push and pull and understanding optimization as a continuous process rather than a one-time event	0.71	Moderate	0.74	Moderate
Visualize the workflow aligning with tangible representation	0.79	Moderate	**0.80**	**Strong**
Training on the pull system (Kanban) as one of many aspects of continuous improvement	0.73	Moderate	0.78	Moderate
Develop KPIs combining causal analysis	0.74	Moderate	0.75	Moderate
Depend on Kaizen culture (feedback loop and learning from mistakes and successes)	0.78	Moderate	**0.80**	**Strong**
Psychological safety to guarantee that feedback and teamwork are effective	**0.84**	**Strong**	**0.85**	**Strong**
Top management commitment	**0.90**	**Strong**	**0.92**	**Strong**
Communication and coordination between all parties	**0.86**	**Strong**	**0.92**	**Strong**

Table 8
Kruskal–Wallis and Mann–Whitney tests.

Variables (definitions after Round 2)	Type of work	Experience
	Kruskal–Wallis *p*-value	Mann–Whitney *p*-value
Effective communication among diverse stakeholders to clarify their demands along the value chain	0.810	0.651
Define value and nonvalue activities within the context of the project or organization	0.652	0.449
Customizing practical and short-term training to the specific context of each client or case	0.107	0.880
Understanding actual variability and how information, materials, labor, and equipment “flow”	0.384	0.651
Establishing clear benchmarks and performance metrics considering a different perspective	0.194	0.413
Process visualization and waste definition training	0.085	0.786
Knowing the differences between push and pull and understanding optimization as a continuous process rather than a one-time event	0.858	0.235
Visualize the workflow aligning with tangible representation	0.714	0.525
Training on the pull system (Kanban) as one of many aspects of continuous improvement	0.080	0.880
Develop KPIs combining causal analysis	0.202	0.651
Depend on Kaizen culture (feedback loop and learning from mistakes and successes)	0.918	0.525
Psychological safety to guarantee that feedback and teamwork are effective	0.131	0.608
Top management commitment	0.506	1.000
Communication and coordination between all parties	0.415	0.288

presented in the proposed LCK framework display similar levels of agreement across the three groups.

Additionally, the Mann–Whitney test was conducted to determine whether a significant difference exists between the responses of experts with less than 20 years of experience and those with more than 20 years. As illustrated in Table 8, the *p*-value for all variables was greater than 0.05, indicating no significant divergence between the medians of the two groups.

5. Discussion and a comprehensive lean construction knowledge framework

This study significantly contributes to the literature by introducing a new framework that includes essential steps for acquiring knowledge regarding LC adoption in companies. Unlike one-dimensional frameworks discussed in the literature [12,23,24,26,28], this framework presents a 4x3 matrix. The matrix format with distinct *x*- and *y*-axes integrates LC knowledge (understanding LC concepts, how to implement them, and the importance of continuous training [5]) with LC principles [37], which have not been discussed in the

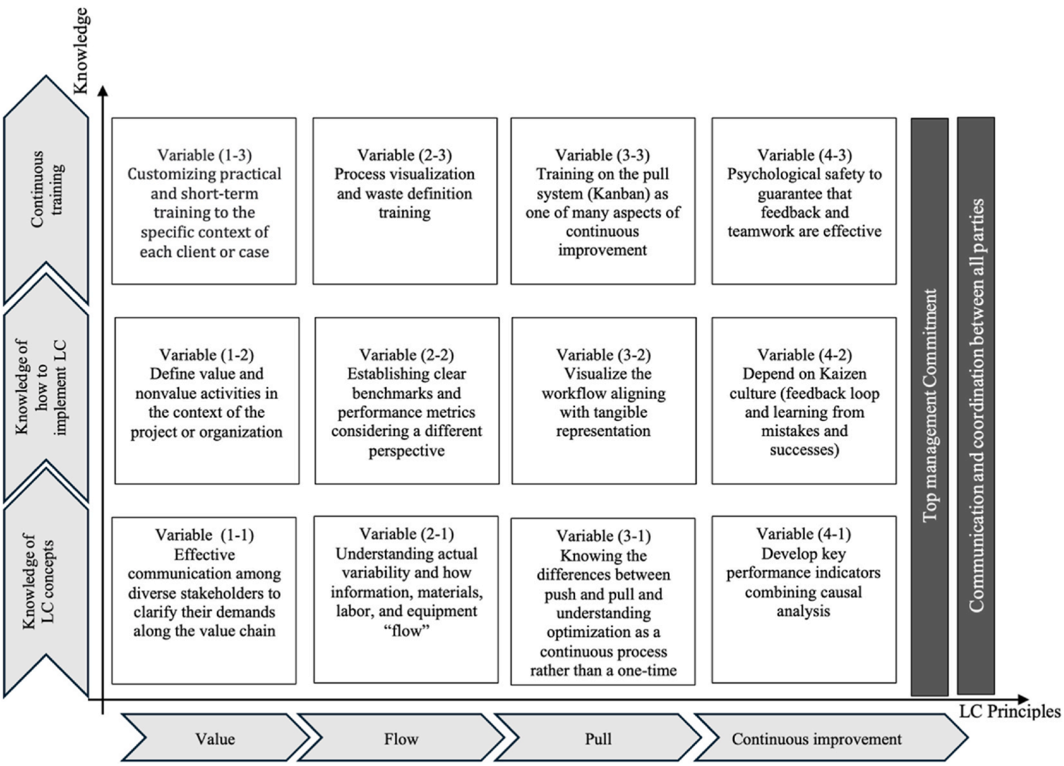

Fig. 3. Final lean construction knowledge (LCK) framework (after Delphi implementation).

literature. This structure improves the reliability of the framework and reflects a higher level of expert consensus, a significant improvement over previous frameworks. The first draft of the framework, as shown in Fig. 1, was developed after a comprehensive literature review and a later pilot study; afterwards, based on feedback from LC experts across two Delphi rounds, the framework was refined to produce the final version shown in Fig. 3.

Quantitative analysis indicates a marked increase in the reliability of the framework from Round 1 to 2, suggesting its robustness and potential utility in future applications [68]. A higher mean value for all 12 variables linking the LC principles and knowledge aspects and the two external variables that enhance the overall framework efficiency from Rounds 1 to 2 indicates an increase in expert consensus. Notably, many experts shifted their opinions to strongly agree in Round 2, reflecting a heightened level of agreement and the perceived importance of these variables. In contrast, despite the varied job types and expertise of the experts, the results of the Kruskal–Wallis and Mann–Whitney tests (Table 8) demonstrate a notable level of agreement regarding framework effectiveness. This uniformity suggests that the framework is robust and applicable across scenarios in the construction sector. Furthermore, essential expert recommendations resulted in significant changes to the original framework, as illustrated in Fig. 3 and discussed below.

5.1. Knowledge of lean construction concepts

Communication between diverse stakeholders, Variable 1-1, is considered a critical component in the proposed LCK framework due to its alignment with the first step of the LC principle (value) regarding gaining knowledge related to LC concepts. Initially, Variable 1-1 was limited to communication with clients or customers. However, following the pilot study and Delphi rounds, the variable was revised to “effective communication between diverse stakeholders to clarify their demands along the value chain.” Reviewers suggested this vital modification in order to include communication with all stakeholders, recognizing that all parties involved in the construction project play a role in value creation. This modification was logical because it reflects the need for comprehensive communication across the entire value chain. The modification was also supported by LC Expert 5, who stated, “Lean construction shows value by focusing on flow rather than only the single activities; hence, communication is needed across the value chain.”

The mean value of this variable after Round 1 was 5.22 (Table 5), indicating a strong agreement among the LC experts. However, the consensus value indicated moderate importance. Additional comments by the LC experts further supported the variable. As Expert 21 noted, “The definition of value itself is essential. It goes beyond defining value-adding activities to include the different ways of understanding value and creating value. A simple addition in this regard is covering the client’s needs and requirements.” Expert 22 stated, “When you talk about effective communication, perhaps you should also highlight the importance of early involvement of contractors and specialist trades.”

These comments align well with Variable 1-1, which was designed to capture a comprehensive understanding of the value, including all the needs and requirements of the stakeholders [12]. This process begins in the initial stages by communicating with stakeholder groups (clients, contractors, subcontractors, special tradespeople, designers, local and national authorities, residents and business owners of the site, politicians, government officials, etc.) to understand their needs and requirements [1]. This strategy helps ensure that all stakeholders agree on the value. In Round 2, experts agreed on this variable with no further suggestions. The mean value increased slightly to 5.35, and the consensus on its importance remained moderate.

In the flow LC principle, understanding the actual variability and how information, materials, labor, and equipment “flow” (Variable 2-1) helps gain suitable knowledge of LC concepts. Gaining this knowledge is crucial to understanding the variability of construction processes and how elements, such as information, materials, labor, and equipment, move along the value chain [39]. Initially, the variable was limited to defining the flow type without specifying it. Expert 21 recommended expanding the variable by suggesting the article “Lean & the Deployment of Robots in Construction” by Alan Mossman [74]. Expert 23 stated, “In my opinion, it is necessary to understand the flow type in different contexts and their impact on productivity.” This recommendation emphasized the need to understand the concept of flow and apply it practically in construction settings. Expert 17 supported this viewpoint, noting that although continuous flow is ideal, the construction industry frequently involves batch production. He stated, “In construction, the workers can move in a continuous flow through the work environment, but this is rarely in fully continuous flow processes because we don’t have a high-volume production of standardized items.” The validity of that comment is acknowledged; however, the variable aims to combine different perspectives and offer a practical framework for enhancing the understanding of LC practices. Acknowledging the variability and customization in construction offers insight into the influence of different flow types on the process, enabling the efficient optimization of these flows.

In contrast, Expert 1 proposed that understanding flow may be less critical for on-site workers, although it is essential for those developing processes and tools, commenting: “Flow can be challenging to understand as a concept. It is needed for those developing processes and tools, but for those working in the industry, this understanding is less needed to succeed.” This perspective suggests that the significance of this variable may differ depending on an individual’s position in the project, despite its importance in acquiring knowledge about LC. When attempting to gain knowledge, the focus is naturally directed toward those who control the processes and tools, as they play an essential role in training on-site workers [19]. After Round 2, Expert 10 claimed that there is a need to “understand actual variability and how information, materials, labor and equipment ‘flow.’” By understanding the different types of flow, process developers can create more efficient systems and tools that directly benefit workers, even if the workers do not require a thorough understanding of the flow [48].

These suggestions refined the focus of the variable, emphasizing the practical aspects of how information, materials, labor, and equipment flow in construction. The improvement is reflected in the mean values of the variable, which improved from 4.91 in Round 1 to 5.35 in Round 2, indicating increased agreement among experts. Following these changes, the consensus on the importance of this variable increased, increasing from low to strong.

In the initial steps of gaining the pull LC principle, the experts provided valuable feedback that significantly informed the approach to refining the variables. For example, Expert 1 stated, “For me, lean is a journey, not a goal. If you believe that lean will fix a problem and you are done, you will most likely fail.” Expert 23 added, “In my opinion, understanding optimization as a continuous process rather than a one-time event is needed, and it is part of continuous improvement. For the first level, you need to differentiate pull and push flows and their impact on the process.” This insight led to modifying Variable 3-1, which links the LC pull principle with gaining suitable knowledge in LC concepts, better reflecting the importance of understanding the differences between push and pull flows and recognizing optimization as an ongoing process. The modified variable was adjusted to “knowing the differences between push and pull flows and understanding optimization as a continuous process rather than a one-time event.” The modification is reflected in the data, with the mean value for this variable increasing from 4.96 in Round 1 (indicating general agreement) to 5.35 in Round 2 (indicating even stronger agreement). Furthermore, the consensus level of importance remained moderate, increasing slightly from 0.71 to 0.74, indicating increased agreement among experts.

Variable 4-1, which is to develop KPIs combining causal analysis, is vital in establishing an essential link between continuous improvement and the knowledge of LC concepts. This variable emphasizes the importance of KPIs as tools that provide a deeper understanding of how LC principles affect overall performance when combined with causal analysis. The KPIs are more than just measurable targets. During the initial round of expert feedback, some experts expressed concerns regarding the potential misuse of KPIs. For example, Expert 23 stated, “For the first step, knowledge about lean construction concepts, it would also be good to add something associated with the causal analysis of problems.” The variable was revised to include causal analysis in response to this concern, guaranteeing that KPIs function as meaningful progress indicators rather than mere metrics. This modification resulted in a moderate increase in the mean value from 4.70 (agree) in Round 1 to 4.96 (agree) in Round 2. The consensus level of importance also slightly improved from 0.74 to 0.75, suggesting moderate importance among the experts.

5.2. *Knowledge of how to implement lean construction*

Variable 1–2 helps learn how to implement LC in alignment with the LC value principle: “define the value and nonvalue activities in the context of the project or organization.” It was modified based on insightful suggestions from Expert 7, who emphasized that “the aim is to achieve Value by identifying it and finding the shortest route to achieve it, not to create further processes.” Defining activities with and without value in a specific environment ensures that efforts are directed toward finding and achieving value immediately and avoiding unnecessary steps [33].

In Tables 5 and 7, LC experts agreed on this variable, with a mean value of 5.04 in Round 1. After modification in Round 2, the mean value increased to 5.57, shifting toward strong agreement among the LC experts. Although the consensus was initially low after Round 1, it became stronger after the variable was modified in Round 2.

Another important variable that helped explain how to implement LC in the flow LC principle was Variable 2-2: establishing clear benchmarks and performance metrics, considering different perspectives. Initially, this variable was considered less important, with a mean value of 4.70 in Round 1 and low agreement on its significance. It was modified based on the suggestion by Expert 1:

> “Benchmarks are nice to have, but they do not need to be [for the project’s success]. Benchmarks are needed to convince managers - not for those working on the project. Here, it is enough to feel you add value, and you have fun. You can achieve knowledge without adding a number to the process”.

While this viewpoint emphasizes the importance of employees feeling valued and engaged, which is critical for implementing LC, clear benchmarks and performance metrics are also required. These metrics provide a theoretical foundation for understanding and effectively implementing LC principles [38]. The variable is modified to strike a balance between the importance of benchmarks and the practical experiences of different project teams. After this adjustment, the mean value increased to 5.17 in Round 2, and the consensus level of importance shifted from low to moderate.

Furthermore, Variable 3-2 helps explain how to implement LC and achieve the pull LC principle focused on “visualizing the workflow aligning with tangible representation.” This variable exhibited an improvement in the mean value, increasing from 5.26 in Round 1 to 5.35 in Round 2, whereas the consensus level of importance increased from 0.79 (moderate) to 0.80 (strong). This change is consistent with Expert 1’s belief that visualization is critical: “Using visualization as boundary objects in the conversation is helpful, and I have not found another means of communication with the same impact.”

Variable 4-2, “depend on Kaizen culture (feedback loop and learning from mistakes and successes),” establishes a connection between knowledge of how to implement LC and continuous improvement. This variable emphasizes the significance of implementing a Kaizen-driven approach involving continuous learning and feedback from successes and failures. The dual focus of this approach was emphasized by Expert 10, who recommended that “You might add … learning from both mistakes and successes.” In response, the variable was refined to emphasize the importance of Kaizen culture in fostering a learning environment that regards all experiences as opportunities for improvement. The consensus level of importance for this variable increased from 0.78 (moderate) in Round 1 to 0.80 (strong) in Round 2, indicating a more substantial consensus among experts regarding its significance. The mean value for this variable remained high at 5.39 (strongly agree) throughout both rounds.

5.3. *Continuous training*

The ultimate step in gaining knowledge related to LC is continuous training. Continuous training in the value of the LC principle is represented by Variable 1–3, which customizes practical and short-term training to the specific context of each client or case. Initially, the focus was broader, but the variable was refined in response to Exert 8's suggestion: "I would add that training has to be practical and applicable in the project in the short term." This comment highlighted the importance of adapting practical and context-specific training so that companies can ensure that LC principles are effectively used in real-world circumstances. In addition, the agreement level and importance of this variable shifted from low to strong after this adjustment.

Variable 2–3, process visualization and waste definition training, consistently gained significant support. This variable highlights the importance of practical training in visualizing processes and defining waste, which is vital for successfully implementing LC principles and continuously gaining related knowledge. The mean value for this variable garnered strong agreement, increasing from 5.13 in Round 1 to 5.39 in Round 2. The consensus on its importance also increased significantly from low to strong.

Additionally, Variable 3-3, training on the pull system (Kanban) as one of many aspects of continuous improvement, helps in continuous training on the pull LC principle. This variable was updated in response to feedback from two experts. Expert 1 stated, "Pull and Kanban are good, but this concept is very difficult to understand, especially in the early stages of design." Expert 10 emphasized that "training on the pull system is needed, but as part of continuous training." The variable was modified to emphasize that although Kanban training is necessary, it should be part of a more extensive continuous improvement process. After this modification, the mean value for this variable increased from 5.17 (agree) in Round 1 to 5.39 (strongly agree) in Round 2. The consensus level of importance remained at a moderate level based on the value increasing from 0.73 to 0.78.

Variable 4-3, psychological safety to guarantee that feedback and teamwork are effective, establishes a connection between continuous improvement and ongoing training by emphasizing the necessity of a secure environment in which feedback can be freely exchanged, and teamwork is encouraged. This connection is essential for ensuring that training programs are implemented and effectively promote continuing improvement [19,43]. Expert 8 underscored the importance of this environment: "Psychological safety is needed; traditional construction practices have taught practitioners to distrust and hide mistakes." In addition, Expert 10 added, "You should incorporate psychological safety, which is promoted by leadership and is necessary to achieve continuous improvement." In response to these awarenesses, the variable was modified to include psychological safety to guarantee that it is acknowledged as a critical component of successful continuous training. The data strongly support this adjustment, as the mean value increased from 5.57 (strongly agree) in Round 1 to 5.65 (strongly agree) in Round 2. The consensus level of importance also maintained its strength, slightly increasing from 0.84 to 0.85.

The LCK framework is considerably influenced by two external variables: top management support and communication and coordination among all parties. In both rounds, the experts equally acknowledged the critical role of these variables, rating them as "strongly agree." Hence, the support of top management offers the requisite leadership, resources, and strategic direction [29]. Similarly, ensuring seamless collaboration throughout the construction process, understanding value, and aligning goals require effective communication and coordination among all stakeholders.

The shared agreement on these external variables emphasizes their critical importance in reaching the desired outcomes in LC. This agreement demonstrates that a successful application of LC principles is unlikely without strong management support and clear, coordinated communication [7]. After these modifications, the experts displayed a stronger consensus, as observed by the higher mean values between rounds, indicating the validity of the proposed LCK framework and its content.

6. Conclusions

6.1. Contributions

Companies initiating LC adoption or aiming to enhance their practices face unique challenges, primarily due to knowledge gaps and the lack of a structured framework. This study addresses this gap by proposing a comprehensive framework for managing LC knowledge tailored to the specific needs of these companies. The relationship between LC principles and LC knowledge aspects was analyzed and validated to achieve this. The literature review identified critical challenges to LC implementation, specifically related to knowledge of LC concepts, their implementation, and the need for continuous training. The proposed LCK framework incorporates 12 variables that link LC principles to the three defined knowledge areas and the two external variables that enhance the overall framework efficiency. These variables were validated using the Delphi technique, involving 23 international LC experts, to ensure the strength and relevance of the framework. The two Delphi rounds resulted in a strong consensus among the expert panel, underscoring the importance of these variables as being foundational to LC implementation. Success hinges on top management support and communication and coordination between all project stakeholders. Each variable is noteworthy and complements the others, even if context-specific, and the proposed framework functions as a cohesive unit.

This framework contributes to the body of knowledge by providing companies with a structured approach, whether they are implementing LC adoption or aiming to improve their existing practices. The framework addresses the specific variables that facilitate LC implementation progress and serves as a practical tool for practitioners and a guide for policymakers and educators, promoting a more supportive environment for LC adoption.

6.2. Limitations

A fundamental limitation of this study is the lack of actual case studies or a practical validation of the proposed LCK framework. Although the framework was developed and validated via expert consensus using the Delphi technique, it has not yet been tested or implemented in construction projects or companies. Hence, the effectiveness and potential challenges of applying the framework in diverse types of companies, whether initiating or enhancing LC adoption, remain uncertain. Without practical validation, the influence of the framework on managing LC knowledge and principles remains theoretical.

6.3. Recommendation for future study

The proposed framework offers a starting point for companies initiating LC adoption or enhancing existing practices. Future studies should validate the framework via practical applications in various companies and assess the feasibility and challenges of implementing it in the construction industry sectors through projects or case studies. Additionally, longitudinal studies should evaluate the long-term influence of the framework on LC adoption and its ability to promote continuous improvement.

CRediT authorship contribution statement

Esraa Hyarat: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization, Investigation, Methodology, Resources, Software, Validation, Visualization. **Laura Montalbán-Domingo:** Writing – review & editing, Supervision, Formal analysis, Data curation, Conceptualization, Investigation, Methodology, Resources, Validation. **Eugenio Pellicer:** Writing – review & editing, Supervision, Formal analysis, Data curation, Conceptualization, Funding acquisition, Investigation, Methodology, Project administration.

Informed consent statement

Informed consent was obtained from all subjects involved in the study using the consent form included in the Supplementary Materials.

Institutional review board statement

This study was conducted under the doctoral thesis work at the *Universitat Politècnica de València*. The project (reference: P06-22-02-2023) received ethical approval from the Research Ethics Committee of the *Universitat Politècnica de València* in its session held on March 22, 2023.

Availability of data and materials

Data supporting the findings of this study will be made available upon reasonable request to the corresponding author.

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Declaration of competing interest

X The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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