Exploring lean practices' importance in sustainable supply chain management trends: An empirical study in Canadian construction industry

Phuoc-Luong Le, Ho Chi Minh City University of Technology (HCMUT) & Vietnam National University (VNU-HCM)
Duy-Tan Nguyen, HEC Montréal, Canada
Corresponding author: Phuoc-Luong Le (lpluong@hcmut.edu.vn)

Abstract: To contend with the current economic conditions, construction managers are recommended to identify sustainable construction supply chain management (CSCM) trends over the forthcoming years and adopt suitable techniques to manage construction projects strategically, tactically, and operationally. However, there is a shortage of studies exploring Lean Construction (LC) practices' contributions to sustainable CSCM trends in the forthcoming years. Thus, this paper applies the integrated fuzzy AHP–Delphi approach to identify key sustainable CSCM trends and uses them as strategic evaluation criteria to assess and rank LC techniques. The evaluation was done by 28 experts having more than four years' experience and expertise in lean construction and sustainable CSCM. This work also provides managerial implications by proposing a framework for LC techniques to advance sustainability throughout construction project phases. The framework leverages the roles of Virtual Design Construction and Last Planner System as strategically important tools for design and architectural engineering and project planning and control, respectively. In addition, the framework aims at the sustainability of on-site construction execution by taking account of LC tools for on-site safety warranty, problem-solving, and continuous improvement.

Keywords: Supply Chain Management, Construction Industry, Lean Construction, Sustainable Construction, Sustainability Trends.

Introduction

The construction sector uses innumerable non-renewable fuels and materials for its processes which produce a huge quantity of carbon emissions (Yu et al., 2020). Further, this industry has been known for such inefficiencies as poor quality, defective design, and inferior conditions of safety and working, which generate non-value-added activities, process uncertainty, and wastage (Bos et al., 2014). There is a lack of effort to establish green and smooth flows for transformation processes from raw materials to tangible construction (Le & Nguyen, 2022). For years, scholars and practitioners have discussed the necessity to change construction practices to increase efficacy. This entails a change in the critical way of construction execution and a deep concentration on managing the entire set of construction processes.

When construction is practiced through maximizing value and minimizing waste, it is called lean construction (LC) (Koskela et al., 2002). LC advances smooth flow and value creation (Sarhan et al., 2019) by coordinating interdependent tasks during the whole project and then reducing nonvalue-added activities. LC also focuses on value creation by boosting customer satisfaction and project participant integration (Carvajal-Arango et al., 2019). Construction management can be improved thanks to LC practices with regard to procurement, scheduling, and control (Al-Aomar, 2012). For over two decades, LC has emerged as one of the most efficient methods to enhance construction performance. Today, LC is regarded as a critical approach to coping with the construction industry's inherent problems (Le & Nguyen, 2022).

Recently, the application of sustainable construction supply chain management (CSCM) advances supply chain (SC) integration to minimize negative environmental impacts, reduce waste and costs, and enhance social issues (e.g., creating a safe and healthy built environment) (Sarhan et al., 2019; Le & Nguyen, 2022). Sustainable CSCM and its application during project activities have attracted the interest of scholars and practitioners to serve the "triple bottom line" (people, the planet, and profit) focusing on social, environmental, and economic dimensions (Solaimani & Sedighi, 2020; Athapaththu & Karunasena, 2018). Sustainable CSCM satisfies social demand for products and services while saving natural resources; hence, it enables productive systems to have safe and efficient transformation of environmental resources into social welfare. This preserves an equilibrium between built and natural environments and promotes social values and sustainable building practices (Carvajal-Arango et al., 2019).

The last decades' research has aroused an interest in two concepts, namely LC and sustainable SCM, as well as suggested that sustainable CSCM can be efficiently promoted and supported through LC practices (Khodeir & Othman, 2018; Sarhan et al., 2019; Solaimani & Sedighi, 2020; Carvalho et al., 2017; Carvajal-Arango et al., 2019). LC practices can contribute to sustainable CSCM in two main aspects. Firstly, by focusing on waste reduction, LC can eliminate material and energy wastage and pollution from construction and maintenance. Secondly, by advancing value creation, LC can simultaneously promote clients' value in economic, environmental, and social terms (Sarhan et al., 2019). Concurrent application of both LC and sustainable CSCM creates more positive impacts than their separate implementation. Indeed, deploying the two philosophies together helps improve client values, optimize resources, and reap greater benefits in construction processes, e.g., lead-time reduction and SC relationship enhancement (CarvajalArango et al., 2019). Also, companies adopting LC for continuous improvement tend to implement environmental and social practices more effectively (Carvalho et al., 2017).

Despite the expected gains from combining LC and sustainable CSCM, their concurrent application has not been fully explored in the industry (Solaimani & Sedighi, 2020; Carvalho et al., 2017). Still, the construction segment lacks inclusive research on how to integrate LC and sustainable CSCM to obtain social, environmental, and economic benefits (Carvalho et al., 2017). Regarding LC application, it necessitates more practical studies on the classification and ranking of lean tools used for construction projects (Le & Nguyen, 2022; Ansah & Sorooshian, 2017) to offer project managers helpful advice on which LC tools to apply throughout the project. It is equally worthwhile exploring the trends of sustainable CSCM to recommend to construction practitioners how to ameliorate sustainable construction performance (Le & Nguyen, 2022). However, there is a shortage of research examining LC practices' contributions to sustainable CSCM trends in the forthcoming years.

Based on the below-reviewed literature, we find that construction firms need to identify the forthcoming sustainable CSCM trends and promote sound practices to run construction projects strategically, tactically, and operationally. Nevertheless, state-of-the-art research in construction management has mostly concentrated on the application of the concept of sustainable SCM while there is a shortage of research, which recognizes and ranks the critical trends of sustainable CSCM. Also, there is a need for research into assessing and prioritizing tools for LC practices to cope with trends in sustainable CSCM. To fill the gaps and cope with practical matters of the construction sector, our study aims to: (i) identify significant trends in sustainable SCM in construction in the forthcoming years; (ii) apply those sustainable CSCM trends as the main criteria for assessing and ranking lean construction tools; and (iii) propose a framework to practice LC tools for construction projects with respect to the trends of sustainable CSCM. The results provide a reference for construction practitioners to rank and apply appropriate lean tools for project operations to advance sustainability in CSCM.

The paper is arranged into six sections. The introduction is presented in Section 1, and the relevant works are then synthesized in section 2. Next, the research method is described in section 3 which comprises the theoretical foundations of the fuzzy AHP–Delphi method. Subsequently, the research results and sensitivity analysis are shown in section 4, whereas section 5 discusses in depth the managerial implications for construction practitioners. Lastly, conclusive points are summarized in section 6.

Literature review

Trends in sustainable management of construction supply chains

Sustainable SCM in construction encompasses the utilization of best practices and clean and resource-efficient techniques for positive environmental and socio-economic performance (Athapaththu & Karunasena, 2018). In sustainable CSCM, sustainable development principles apply across construction project phases from planning and design through construction to final deconstruction and waste management (Athapaththu & Karunasena, 2018; Le & Nguyen, 2022; Kosanoglu & Kus, 2021). Indeed, to achieve sustainable CSCM, sustainability policies and practices such as green purchasing, green logistics, and green and cleaner production should be implemented (Kosanoglu & Kus, 2021). The following subsections present the trends of sustainable SCM in the construction sector.

Trends of sustainable construction standards and measurements: Sustainability policies must be considered from the very beginning of building configuration to ensure that its development meets sustainability requirements. Specific policies, which cover *sustainability standards and guidelines*, should be enacted to enable construction firms to foster sustainable development, address current societal challenges, and increase their competitiveness (Athapaththu & Karunasena, 2018; Kylili & Fokaides, 2017). Government policies should aim at both short-term and long-term actions to provide investment and business opportunities as well as enhance human-capital resources (Kylili & Fokaides, 2017). In the scope of construction enterprises, research, development, and innovation activities should focus on best practices aligned with the legislation and regulations concerning sustainability. Required to have their buildings certified with respect to environmental, economic, and social sustainability, companies must take account of sustainability issues within their vision and mission. The standards and guidelines for sustainable construction that firms need to consider address quality, workplace, health, safety, and social issues as well as environmental, financial, and open communication policies. These standards and guidelines have a strong impact on the sustainable construction performance of enterprises (Athapaththu & Karunasena, 2018).

Along with standards and guidelines, sustainability *measurement and reporting* are critical to sustainable construction development (Holton et al., 2010). Companies are advised to adopt a system of measurement and reporting or apply current benchmarks to appraise and improve environmental, social, and economic performance (Tan et al., 2011; Pitt et al., 2009). Athapaththu and Karunasena (2018) stated that project benchmarking and sustainability assessment tools assist contractors to work toward sustainable construction.

Trend of SC integration for sustainable construction: During the last decades, scholars have suggested SC integration as a feasible way to deal with existing problems in the construction industry (Abdirad & Krishnan, 2021; Ho et al., 2019; Le et al., 2021; Nguyen & Le, 2022). SC integration enabled by commitment and communication among SC members provides necessary information for decision-making (Nguyen et al., 2021, 2022). This improves the efficiency of construction planning and development and lessens the risk of SC participants' non-compliance (Nguyen & Le, 2022). Kosanoglu and Kus (2021) pointed out that SC integration promotes SC actors' responsibilities in delivering a sustainable construction supply chain (CSC). Architects and engineers participate in building designs while owners and main contractors perform central roles in developing and financing sustainable construction projects (Le et al., 2021). Therefore, CSC integration plays an integral role in diminishing the malign influences of construction activities on local communities and the environment. In effect, CSC integration correlates positively with sustainable construction, and it is worth advancing CSC integration for sustainability purposes (Zeng et al., 2018).

Trends of sustainable construction functions (design, digital transformation, and procurement): Construction designers have been continually seeking methods and tools to reduce energy consumption and environmental effects to achieve more efficient and sustainable buildings (Liu et al., 2017). *Sustainable design* has become an emerging trend in the construction industry with recently high demand for sustainable construction design (Elbeltagi et al., 2017). To keep up with this trend, such approaches as Building Sustainability Assessment and Building Information Modeling (BIM) have been used to facilitate designers' decision-making on environmental, social, and economic issues (Maltese et al., 2017; Carvalho et al., 2021). Sustainability requirements and measures should be examined and integrated in the preliminary design so that sustainability tools can exert more influence on project activities and building sustainability (Carvalho et al., 2017).

Another trend of sustainability in construction is *digital transformation* which takes information and communications technologies to change core processes in construction projects (Abioye et al., 2021). Due to its transformational power, digital transformation is regarded as a critical enabler of environmentally sustainable development. To achieve sustainability, construction projects must deal with such concerns as wastage, safety hazards, and economic issues (Wernicke et al., 2021). Digital transformation technologies can change the construction industry's status quo through such approaches as Construction 4.0 (García de Soto et al., 2022). The sector has increasingly embraced digital technologies, especially BIM to boost CSC collaboration and project performance (Whyte, 2019; Hall et al., 2020).

The other important function is *construction procurement,* which has significantly contributed to building sustainability through the insertion of environmental protection, societal progress, and economic development in procurement processes (Brammer & Walker, 2011). Governments and organizations around the world have been recommended to promote policies and practices for sustainable procurement (Yu et al., 2020). Sustainable procurement can lead to resource efficiency, high quality, and cost minimization across the product lifecycle (Ramkumar & Jenamani, 2015). Green procurement practices, strategies, and measures to ensure the prevalent and rapid adoption of sustainable procurement have been increasingly implemented for construction performance improvement (Meehan & Bryde, 2015; Eriksen et al., 2017; Yu et al., 2020).

Trends of sustainable construction education and innovation: Aware of the role of education in accomplishing sustainability in construction projects, construction companies tend to have more commitment to sustainability through the improvement of staff *education and training* (Liang et al., 2014; Tan et al., 2011). Not only the workforce but also relevant CSC actors such as suppliers and subcontractors need to partake in training programs on sustainable construction (Athapaththu & Karunasena, 2018). Further, enterprises can reach a higher sustainability level for construction processes through the *innovation* of sustainable technologies employed for process improvement (Tan et al., 2011; Liang et al., 2014; Booth et al., 2012). Construction firms are acutely conscious of the importance of such technologies and have used them to reduce wastage, recycle materials, preserve water and energy, conserve biodiversity, and sustain cost-effectiveness (Tan et al., 2011; Athapaththu & Karunasena, 2018). It is noted that clients' requirements also prompt contractors to apply sustainable technologies, innovations, and processes.

Trends of sustainable construction execution (cleaner onsite and offsite construction, reverse logistics): Onsite construction logistics has focused on material handling and site layout planning which are closely interrelated (Hammad et al., 2016; Ning et al., 2010; Ning et al., 2016). Building construction necessitates strenuous exertions to transport, store, assemble, and arrange building materials in a limited site space using suitable construction technologies. A productive site layout enables material handling with smooth material and equipment flows, thus promoting the safety and efficacy of construction project execution. During the past decades, scholars have investigated many tools and aspects of *cleaner and sustainable onsite construction*, such as noise reduction for various surrounding receivers (Hammad et al., 2016), safety and environmental concerns for onsite operations (Ning et al., 2010), and external transportation and safety as principles for layout selection (Ning et al., 2016).

With the growing employment of offsite technologies for modularization and prefabrication, the complexity of managing materials supply for construction projects has substantially increased. Therefore, along with the utilized technologies, the management of supply configurations is also critical for the improvement of offsite prefabrication performance. For years, multiple managerial approaches have been pursued for *cleaner offsite construction* logistics and SCM such as precast scheduling, lean methodology, supply decisions and configurations, and disturbance evaluation (Arashpour et al., 2017; Im et al., 2009; Liu & Lu, 2018; Wang et al., 2018).

Researchers have demonstrated that *reverse logistics* applied in construction can bring many advantages, from positive environmental effects to economic and social benefits (Chileshe et al., 2015; Rameezdeen et al., 2016; Rahimi & Ghezavati, 2018). Although the environmental and social advantages of reverse logistics are highlighted in government regulations, its economic benefits, e.g., cost savings, act as the main incentive for construction practitioners to adopt reverse logistics (Hosseini et al., 2015). Reverse logistics has become an emerging trend in construction projects; thus, there are calls for further qualitative and quantitative research to explore its benefits and leverage the roles of relevant CSC stakeholders.

Trends of safety and risk management for sustainable construction: *Safety and social sustainability* is an important trend for sustainable construction, which addresses work settings, employee rights, social missions, training and education, diversity and equality, and health and safety (Dallasega & Rauch, 2017; Solaimani & Sedighi, 2020; Kosanoglu & Kus, 2021). Safety and social sustainability in CSCM focus on raising staff satisfaction and living standards through creating safe working conditions and upholding employee rights (Kosanoglu & Kus, 2021; Tsai et al., 2021). In addition, *risk management* serves an essential role in detecting and reducing CSC risks to guarantee safety and social sustainability in construction projects. Risk management in construction requires close collaboration among different stakeholders in construction design and execution (Mofidi et al., 2020; Newaz et al., 2021). Risks exist across construction project phases, e.g., design-related, supplier-related, delivery-related, and operational risks. Okudan et al. (2021) suggested focusing on efficient exploitation of risk-based knowledge, such as risk mitigation lessons learned from previous projects, and consequences and efficiency of response strategies for risk management.

Exhibit 1. Review of trends in sustainable CSCM.

The summary of trends for sustainable CSCM is presented in **Exhibit 1**. Overall, there is a shortage of research that utilizes industry experts' inputs to assess and rank trends in sustainable CSCM for the forthcoming years, whereas construction practitioners need to consider those trends to prepare strategic plans for sustainable construction and competitive advantages.

Lean practices in construction

Lean construction (LC) practices are defined as the tools whereby the lean philosophy is adopted for construction project activities: design, planning, and execution (Babalola et al., 2019; Le & Nguyen, 2022). LC tools, which aim to improve project performance (Ansah & Sorooshian, 2017), can be deployed separately or together (integrating many tools) (Aslam et al., 2022; Babalola et al., 2019). LC tools can be classified based on their application to each project phase, e.g., design & engineering, project planning & control, and construction execution operations (Le & Nguyen, 2022). Babalola et al. (2019) recommended that LC tools be classified into four main types based on their application: (i) lean techniques for design & engineering; (ii) lean techniques for project planning & control; (iii) lean techniques for onsite construction; and (iv) lean techniques for safety & health. LC practices are followed in various ways, from using tools for process standardization of a specific stage to handling the whole construction project. **Exhibit 2** illustrates the LC tools most commonly recommended for the industry in recent scholarship.

Exhibit 2. Review of the utmost applied tools for practices of LC.

Lean architectural engineering and design techniques: Construction projects commence with architectural design & engineering which calls for efficient tools to boost performance. The most used tool for this phase is virtual design construction (VDC) which uses many computer-based simulation and design tools to test errors and finalize designs for prefabrication and execution (Babalola et al., 2019). Currently, BIM is a dominant VDC approach to providing n-D models and performing simulations during the design phase (Le & Nguyen, 2022). **Exhibit 2** also presents different tools for the practices of this phase including design structure matrix (DSM), design workshops (DW), prefabrication & modularization (P&M), integrated project delivery (IPD), detailed briefing (DB), target value design (TVD), standardization, construction process analysis (CPA), concurrent engineering (CE), smart goal (SG), team preparation (TP), and Jidoka (Aslam et al., 2020; Babalola et al., 2019; Rybkowski et al., 2022). Among those tools, IPD is a tool for project delivery that focuses on SC integration to improve project performance (Le & Nguyen, 2022). IPD enlists key SC members' early involvement in decision-making and control such that they can cooperatively set project goals and facilitate risk-sharing between SC actors (Babalola et al., 2019). IPD helps resolve existing construction problems, e.g., truncated productivity, excessive cost and duration, rework and wastefulness, as well as ineffective information sharing (Roy et al., 2018). Another vital LC tool is CE, a systematic approach to information sharing between SC partners to produce integrated designs for products and their associated procedures (Shouke et al., 2010). CE guarantees that critical decisions are supported by interdependent engineering crews who consider product details for efficient process designs. Practical evidence shows that CE can foster a collaborative working environment that leads to turnaround time reduction and error elimination across the whole project delivery process (Babalola et al., 2019). Similarly, DW can be organized onsite for architectural designers to evaluate the whole product and process designs so that creative ideation for design solutions can be facilitated (Babalola et al., 2019). In these workshops, related actors (e.g., end-users, funders, or authorities) can communicate with design teams, and then integrate clients' values into architectural designs (Thyssen et al., 2010). In regard to standardization, this technique establishes the scope and standards for each building component in conjunction with its related activities (Babalola et al., 2019). Meanwhile, P&M support the subdivision of prefabricated components into equivalent repetitive modules, which results in the simplification of product designs. According to Rocha and Kemmer (2018), those tools enhance construction performance, facilitate design customization, and reduce wastage.

Lean project planning and control techniques: Also listed in **Exhibit 2** are the common tools for lean practices in project planning and control proposed by previous literature including last planner system (LPS), location-based management system (LBMS), daily cluster/huddle meeting (DC/HM), work structuring & scheduling (WS&S), Benchmarking, bottleneck analysis (BNA), pull scheduling/planning (PS/P), value stream mapping (VSM), Poka-Yoke, line balancing (LB), multi-process handling (MPH), continuous flow (CF), and FIFO line (Babalola et al., 2019; Le & Nguyen, 2022). Among them, the LPS, which is an effective lean practice for project planning and control, advances SC stakeholders' partnering for construction project planning and delivery (Perez & Ghosh, 2018). The LPS assimilates the following functions: (i) master planning for project delivery standard-setting; (ii) phase planning for task assignment in a definite timeframe with cooperative reverse scheduling; (iii) look-ahead planning using restraint analysis and cooperative job design for the creation of the next-four-to-eight-week schedule; (iv) planning for weekly activities using look-ahead plans and reviewing weekly work (AlSehaimi et al., 2014). Meanwhile, VSM defines the current state of processes and helps effect desired improvements to their future state. VSM raises productivity by reducing redundant activities and enhancing needed processes and activities (Le & Nguyen, 2022; Ramani and KSD, 2019). Another tool used for work uncertainty reduction is WS&S, which divides construction processes into consecutive smaller and discrete parts (Al-Aomar et al., 2012). With Benchmarking, criteria are set to motivate construction teams by encouragement packages to complete construction works and then benchmark each other to achieve better performance (Babalola et al., 2019). According to Aslam et al. (2020), DC/HM is another tool to support team problem-solving by organizing meetings for all project managers and construction workers to debate related issues, thus boosting interaction among SC stakeholders (Le & Nguyen, 2022).

Lean onsite construction operations techniques: **Exhibit 2** also presents twenty-one tools for onsite construction management proposed by recent scholars, namely Gemba or Muda walk (GW/MW), 5S, total productive maintenance (TPM), Kanban system, teamwork & partnering (T&P), Kaizen, first-run study (FRS), Just-in-Time (JIT), visual management (VM), conference management (CM), check points & control points (CP&CP), failure mode & effects analysis (FMEA), 5 whys, plan-do-check-act (PDCA), quality function deployment (QFD), setup reduction (SR), 7 basic tools (7BT), statistical process control (SPC), suggestion scheme (SS), and time & motion study (T&MS) (Ansah & Sorooshian, 2017; Le & Nguyen, 2022; Aslam et al., 2020). CM and T&P are recommended to strengthen the relationship and interaction between construction actors on site. CM can be implemented to organize training workshops for project execution and coordination while T&P can integrate related SC stakeholders, e.g., clients/owners, contractors, designers, and suppliers, to boost operational performance in construction sites (Babalola et al., 2019; Johansen & Walter, 2007). Meanwhile, GW is recommended for onsite problem-solving by examining and ascertaining the root causes (Le & Nguyen, 2022). Moreover, FRS is undertaken to model and improve critical building processes since it can detect errors and develop suitable solutions for error prevention and mitigation. Finally, according to Aslam et al. (2020), 5S and Kaizen can encourage the continuous improvement of building processes by attempting to create good onsite working conditions.

Lean safety and health management techniques: As can be seen in **Exhibit 2**, safety and health management in construction sites can apply three practices: fail-safe for quality & safety (FSQ&S), health & safety improvement management (H&SIM), and plan of conditions and work environment (PC&WE) (Babalola et al., 2019). Those practices improve safety in construction sites, including employee safety, by predicting possible risks and taking preventive measures. As such, they support process variability reduction, defect control, and safety assurance (Babalola et al., 2019; Le & Nguyen, 2022).

Though previous research had noteworthy contributions to LC practices, they mostly focused on the application of lean tools to enhance building processes and project performance. There remains a shortage of research assessing and ranking tools for sustainable LC practices deployed in construction projects.

Contributions of LC practices to sustainable CSCM

Sustainable CSCM attempts to obtain economic, environmental, and social benefits through SC integration, efficient resource allocation, minimized energy consumption, and materials reuse (Kibert, 2016). As a result, it yields an improvement in productivity, safety, and health situations in construction sites (Jamil & Fathi, 2016). Meanwhile, LC practices focus on the application of lean approaches and tools to continuously improve building processes, taking into consideration employees' contributions to waste and time reduction, productivity and quality enhancement, cost savings, and customer value maximization (Le & Nguyen, 2022). Many shreds of evidence show the association between LC practices and sustainable CSCM, e.g., both approaches adopt waste reduction as their main characteristic. LC practices can help construction firms eliminate material and energy waste due to ineffective use of resources. Therefore, LC practices contribute to the environmental and economic performance of sustainable construction through waste reduction (Verrier et al., 2015; Carvajal-Arango et al., 2019). Also, the application of LC can create safe and healthy working environment for onsite staff. The human factor is significant for LC implementation. Indeed, lean tools, (e.g., 5S, VSM, or Kaizen) can support employees' welfare, provide better health and safety conditions, and clean construction workplaces (Le & Nguyen, 2022). Using LC practices (such as LPS, 5S, visual management, and error-proofing) can reduce organizational pressure, excessive stress, human errors, and poor working conditions (CarvajalArango et al., 2019).

As such, LC practices can contribute to all three dimensions of sustainable CSCM, namely economic, environmental, and social aspects (Carvajal-Arango et al., 2019). From an economic viewpoint, LC practices can boost organizational innovation capabilities (Solaimani & Sedighi, 2020) for long-term sustainable development. Also, the LC approach can leverage the application of advanced 4.0 technologies, such as BIM, IoT, and Virtual/Augmented Reality, to enhance CSC partners' communication (Solaimani & Sedighi, 2020), which in turn leads to a broader mutual understanding across the CSC (Ashenbaum et al., 2020). From a social perspective, lean human resource management plays a crucial role in achieving social sustainability with more empowered and satisfied employees (Tsai et al., 2021; Kosanoglu & Kus, 2021). In respect of the environment, LC practices facilitate the usage of available local construction materials, techniques, and human resources, thereby reducing ecological wastes. Nevertheless, the state-of-the-art research has not focused on identifying and ranking critical tools for lean practices in construction projects to achieve CSC sustainability. Hence, it necessitates a study to recognize sustainable CSCM trends and use them to suggest appropriate LC practices for the forthcoming years.

Research design

Given the dearth of studies on the contributions of lean practices to CSCM trends (Le & Nguyen, 2022), it is advisable to consult industry experts for initial theory-building in the field as well as for interdisciplinary issues that solicit analyses of emerging trends (Akkermans et al., 2003). In this paper, we adopted the Delphi method and fuzzy AHP approach given their advantages in synthesizing inputs from multiple experts (Akkermans et al., 2003) and handling the subjectivity and ambiguity of human judgments (Dobrosavljević & Urošević, 2022; Singh et al., 2018), respectively. Next, we performed sensitivity analysis to retain the most robust LC techniques that remained consistently above the cutoff threshold despite changes in the weights of the evaluation criteria. These LC practices were inputs for our conceptual framework which integrates lean tools for sustainable CSCM. All the methodological steps of the work are summarized in Exhibit 3.

Exhibit 3. Summary of methodological steps

Delphi and Fuzzy AHP approach

Delphi technique

The Delphi method is implemented by deploying a structured communication where experts share individual opinions anonymously and then reflect on the synthesized results to decide whether to adjust their prior assessment (Linstone & Turoff, 1975). As such, this research method has several advantages. First, anonymous communication encourages participants to develop and share more ideas with the group (Amirghodsi et al., 2020; Le & Nguyen, 2022). Also, this communication structure avoids biases toward influential or well-known participants since viewpoints are shared anonymously. This implies that no individual participant can manipulate the development of the communication process. Finally, according to Akkermans et al. (2003), the Delphi technique allows broadening our understanding of a specific domain where scant data hinder other analytical methods from recognizing certain problems. Therefore, this method is deemed appropriate to our research context.

Expert selection

Following Akkermans et al.'s (2003) admonition, we strived to have a minimum of 20 experts partake in our study so that individual biases that would possibly influence the communication results could be avoided. Many Delphi-based studies invited both scholars and practitioners to gain a holistic view of the problem in question (e.g., Le & Nguyen, 2022). In keeping with previous papers, we invited both experienced academics and practitioners in LC and CSCM to join the Delphi-based communication process. The experts invited must: (i) have more than four years' experience; (ii) have expertise in lean construction and sustainable CSCM, and (iii) be willing to participate in our study. The academic group consisted of professors and researchers at different universities and institutions in Canada. Based on the statistics on Canadian construction firms released on *www.statcan.gc.ca* (a Canadian government website), we invited relevant construction practitioners in Central Canada. In late 2019, we sent invitations to 150 enterprises in *Québec and Ontario* to enlist their participation. In the invitation, we described the objectives of our research and the relevant concepts and practices of LC and sustainable CSCM. Only 20 representatives from the invited firms accepted our invitation, whereas the others declined our invitations for two reasons: (i) their companies neither practiced LC nor had sustainable SCM expertise; (ii) they did not have time. Therefore, we had eight academics and 20 construction practitioners as participants in our Delphi-based research. With approximate probabilities of 70% and 30% respectively, we then applied random sampling to these groups of practitioner and academic participants. The proportion of practitioners selected was larger as our exploratory work focused on the practical benefits of LC and sustainable SCM in improving construction project performance. Participants' backgrounds are summarized in **Exhibit 4**.

Exhibit 4. Participants' backgrounds

Delphi procedure

We applied the Delphi technique in five rounds. First, we clarified the terminology of sustainable CSCM and LC practices in question to avoid participants' misunderstanding or misinterpretation of the terms. Then, these participants identified prevailing trends of sustainable CSCM practices for the upcoming years. Next, they assessed the weights of each trend. Afterward, based on the weights of the key sustainable CSCM trends arising from the previous step as strategic criteria, lean tools were evaluated. For each trend, participants were asked to assess the lean tools' level of contribution to each key trend in terms of improving business performance. The question was sent to participants as follows: "For each trend, please use Saaty's (1980) nine-point scale (which is explained in the evaluation form) to compare each pair of the following lean tools with regard to their contributions to the concerned trend in terms of improving business performance." Finally, we discussed the results with the experts and listened to their feedback. The participants partook in a five-round conference rather than fill out questionnaires by return (e)mail. Each round entailed evaluating the consistency level among the participants to attain a consensus prior to proceeding to the round that ensued. The final round was carried out to discuss the results and consider if a consensus was reached.

The Delphi approach particularly requires that individuals' opinions be received and processed fast and steadily to stimulate further group communication (Akkermans et al., 2003). Held by the research team, the conference which all participants must join was concluded in early 2020. All experts' feedback was anonymous, and their evaluation scores were analyzed by *Expert Choice* (a decision support software package).

In this work, we combined the Delphi method with the fuzzy AHP (Analytic Hierarchy Process) to assess the vitality of the new concepts (sustainable CSCM trends, LC practices, etc.) explored via semi-structured interviews and assessment sheets. All the rounds aforesaid will be discussed in detail in section "Integrated Delphi – fuzzy AHP process."

Delphi integrated with fuzzy AHP

Our study employed the Delphi method to ascertain the key sustainable CSCM trends which were then leveraged as strategic criteria to assess the lean tools utilized for construction projects. Hence, in addition to the Delphi technique, our work entailed multi-criteria analysis to assess each LC tool. Among the widely implemented techniques for multi-criteria decision-making is the AHP (Dobrosavljević & Urošević, 2022), which has been frequently used by scholars in construction (see Le & Nguyen, 2022 for more examples). Yet, given the subjectivity and vagueness of human judgments, it is advisable to adopt the fuzzy set theory, which is incorporated in the fuzzy AHP to address the inability of the conventional AHP to handle ambiguity (Dobrosavljević & Urošević, 2022; Singh et al., 2018). In effect, we opted for triangular fuzzy numbers, instead of precise numbers, to indicate the relative importance of each pair of lean tools evaluated by the participants (Dobrosavljević & Urošević, 2022; Singh et al., 2018) to tackle the vagueness of human judgment and enhance the robustness of our analysis.

In the recent literature in the construction sector, several prior studies combined the fuzzy AHP with the Delphi method. For instance, Khanzadi et al. (2020) used the Delphi method to determine key performance indicators (KPIs) of Iran-based construction projects and the BIM capabilities associated before adopting the fuzzy AHP to prioritize them. Likewise, Gunasekara et al. (2021) developed a model where performance measures resulting from the integrated Delphi – fuzzy AHP are used for contractor selection. Another example is the study of Tamošaitienė et al. (2021) which implemented the integrated Delphi – fuzzy AHP to identify selection criteria and rank repair and maintenance methods for commercial buildings. Searching the Web of Science, which has been widely used for literature retrieval in review papers (Nguyen et al., 2022; Nguyen & Le, 2022), we found an upward trend in the number of journal articles combining the Delphi technique and fuzzy AHP for research in construction and civil engineering (**Exhibit 5**). In fact, the number of studies integrating the Delphi method and fuzzy AHP after 2020 outstripped the figure for the preceding decade (**Exhibit 5**).

Exhibit 5. Combined Delphi – fuzzy AHP in research on construction management

Given the advantages and increased use of the integrated Delphi – fuzzy AHP in the recent construction management scholarship, we deployed this methodology for our work.

The conversion into fuzzy numbers in our work followed Khanzadi et al. (2020). For example, the linguistic scale of importance "*moderately preferred*" was converted into a triangular fuzzy number set (1, 2, 2) (see Khanzadi et al., 2020 for more details). Given two fuzzy numbers $\tilde{U} =$

(a_u, b_u, c_u) and $Z = (a_z, b_z, c_z)$ with $a_u \leq b_u \leq c_u$ and $a_z \leq b_z \leq c_z$, we have $\tilde{U} + Z = (a_u + a_z, b_u +$

$b_z, c_u + c_z)$, $\tilde{U} \times Z = (a_u \times a_z, b_u \times b_z, c_u \times c_z)$, $U\_\tilde{Z} = (ac z\underline{u}, bb\underline{u}z, ac\underline{u}z)$ and $Z\_\tilde{\imath} =$

1 1 1

$\left(\frac{}{c_z},\frac{}{b_z},\frac{}{a_z}\right)$.

Saaty (1980) developed the AHP as a decision support technique which leverages pairwise comparisons among various criteria. These pairwise comparisons result in matrix $\mathbf{M}_{|N|\times|N|}$, where N is the set of items under analysis (LC tools in our work) and $\mathbf{M}_{ij}$ $(i, j \in N)$ indicates how important item i is vis-à-vis item j, e.g., equally important. In the fuzzy AHP, each element of $\mathbf{M}$ is a fuzzy number. In other words, $\mathbf{M}_{ij}$ is a fuzzy number and $\mathbf{M}_{ij} = \mathbf{M}_{ji}^{-1}$.

Then, based on experts' judgments, we followed the fuzzy AHP of Singh et al. (2018) and Geng et al. (2022) to weight and rank each item in order of importance as follows:

Step 1. For each $k \in N$, we compute fuzzy number S_k:

$$S_k = \left(\sum_{j\in N} \mathbf{M}_{kj}\right) \times \left(\sum_{i\in N} \sum_{j\in N} \mathbf{M}_{ij}\right)^{-1} \tag{1}$$

Step 2. For $i, j \in N$, we have fuzzy numbers $S_i = (S_{il}, S_{im}, S_{iu})$ and $S_j = (S_{jl}, S_{jm}, S_{ju})$ as computed in the previous step. We determine the degree of possibility that $S_i \geq S_j$ $(V(S_i \geq S_j))$ as follows:

$$\begin{cases} V(S_i \geq S_j) = 1, \text{ if } S_{im} \geq S_{jm} \\ V(S_i \geq S_j) = 0, \text{ if } S_{iu} \leq S_{jl} \\ V(S_i \geq S_j) = hgt(S_i \cap S_j) \end{cases} \tag{2}$$

$$hgt(S_i \cap S_j) = \frac{S_{iu}-S_{jl}}{(S_{iu}-S_{im})+(S_{jm}-S_{jl})} \tag{3}$$

Step 3. We calculate the weight of each item

$$w'(i) = \min_{j\in N\setminus\{i\}} \{V(S_i \geq S_j)\} \tag{4}$$

Step 4. We normalize the weight vector $W_{|N|\times 1}$ as follows

$$W_i = \frac{w'(i)}{\sum_{j \in N} w'(j)} \qquad (5)$$

This four-step procedure was repeated to quantify the importance of each LC tool in each sustainable CSCM trend $t \in T$ to obtain $\mathbf{W}_{|N|\times|T|}$, where $\mathbf{W}_{it}$ indicated the importance of LC tool i in sustainable CSCM trend t. With sustainable CSCM trends as strategic criteria and their weight vector $C_{|T|\times 1}$ attained in line with the approach of Le and Nguyen (2022), we calculated the overall score of each tool by $\mathbf{W}_i^{\top} C$ . .

Integrated Delphi – fuzzy AHP process

At first, the research team constructed the "*research base*" that clarified the framework and the details that participant experts would be inquired about. The purposes of the conference day were presented to all participants to avoid both misunderstanding and ineffective participation. To reach these objectives, the research team organized the conference in five rounds as follows:

- The first round was called *Clarifying terminology* where the host briefly explained the terms of sustainable CSCM and LC practices in question so that all participants properly comprehended the terminology. These explications are provided in the summary of this paper's literature review.
- The second round was *Identifying key sustainable SCM trends in construction over the upcoming years*: Evaluation sheets built on the research team's literature review were sent to the experts who were then inquired about the vitality of the 13 trends in the handouts in influencing their company's performance in the upcoming years. The evaluations built on a Likert scale from "*Not important*" (1) to "*Extremely important*" (5). Still, participants could also add and evaluate other trends that they deemed important in the construction sector. Their feedback was collected individually and anonymously to avoid biases toward

influential or renowned experts and thus promote feedback diversity (Le & Nguyen, 2022). Statistics (e.g., frequencies, means, and deviations) on these assessments were produced then. In compliance with Rayens and Hahn (2000), the interquartile deviation (IQD) or, in other words, the discrepancy between the 25th and 75th percentiles was calculated to assess the consensus on participants' assessments in this round. The IQD correlates negatively with the consensus level. Given the Likert scale adopted, if the IQD is no greater than 1.000, we can rest assured that a consensus has been reached (Gracht, 2012). As can be seen in **Exhibit 6**, no IQDs were greater than 1.000, indicating consensus among the participating experts. The trends whose means were below *2.5* out of *5.0* were excluded from subsequent analyses because they were regarded as less important trends in the sector. Thus, there were seven CSCM trends (printed in boldface in **Exhibit 6**) retained for Round 3.

Exhibit 6. Assessment of sustainable SCM trends in construction

- The third round: *Weighting key sustainable CSCM trends*: **Exhibit 7** depicts how the key sustainable CSCM trends identified along with LC tools were stratified in this work. The top dashed box illustrates the key sustainable CSCM trends identified as strategic criteria to evaluate LC tools, which are demonstrated at the bottom in dashed boxes corresponding to their categories. The experts were inquired about the relative importance of each pair of the seven sustainable CSCM trends identified. These pairwise comparisons were drawn via Saaty's (1980) nine-point scale and analyzed by *Expert Choice*. Provided in **Exhibit 8** are the rank and weight of each key sustainable CSCM trend arising from the aforementioned analyses. **Exhibit 8** also indicates consistency among experts' assessments given that the consistency ratio (CR) was below the *0.100* thresholds.

Exhibit 7. The AHP structure for analysis in this work

- The fourth round: *Evaluating lean construction practices on sustainable CSCM trends identified as strategic assessment criteria*: Evaluation sheets resulting from the research team's literature review on LC tools were handed out for the participants' assessment. Despite a great many possible lean tools in the literature, only 30 tools were chosen for expert evaluation in this work because they had been proved effective in prior studies for the construction segment (Babalola et al., 2019; Le & Nguyen, 2022). The selected tools belong to four groups, namely design & engineering, project planning & control, (onsite) construction execution management, and safety management (cf. Le & Nguyen, 2022). As the construction industry differs from its manufacturing counterpart by its fragmented and project-based nature, expert assessment is needed to exclude unsuitable lean techniques. Via Saaty's (1980) nine-point scale, the participants in this round were afresh asked to compare the relative importance between each pair of the 30 LC techniques in each key trend of sustainable CSCM identified in Round 2. As such, the seven trends of sustainable CSCM identified were leveraged as strategic assessment criteria to compare LC tools: o For each key sustainable CSCM trend, the importance of each LC tool which was calculated using the fuzzy AHP is provided in **Exhibit 9**. The consistency ratios

  (CRs) were all below the 0.100 threshold, indicating consistency among experts' assessments.

  - The research team used the "*post-group consensus*" method to measure the level of agreement among the participant experts to the synthesized result (Gracht, 2012). Indeed, these aggregate results were presented to all participants, who then justified these results individually. The upshot was that all experts expressed their approval.

Exhibit 8. Weighting and ranking sustainable SCM trends in construction

- The final round was *Result Discussion*: In this round, the research team listened to the participants' opinions on the results, notably on LC techniques that can ameliorate CSCM performance efficiently for the forthcoming years. We leveraged their ideas as a basis for managerial implications for LC practices.

Sensitivity analysis

In keeping with Scala and Pazour (2016), we conducted sensitivity analysis to study how changes in the weights of the evaluation criteria would alter the ranking of the LC practices in question. In other words, sensitivity analysis helps investigate the stability of the ranking results (Mangla et al., 2015; Alamdari et al., 2022). Thanks to sensitivity analysis, we can determine the most robust items that stably remain above the cutoff threshold notwithstanding changes in the weights of the assessment criteria. Following Yazdani-Chamzini and Yakhchali (2012), Scala and Pazour (2016), and Alamdari et al. (2022), we conducted the sensitivity analysis as follows:

$$w_{i,new} = w_{i,old} \times t,\ t = 1.5,\ 2.0,\ 3.0,\ \dots,\ t_{Max} \qquad (6)$$

$$w_{j,new} = w_{j,old},\ j \in I \setminus \{i\} \qquad (7)$$

$$w_{i'} = \frac{w'_{i,new}}{\sum_{j' \in I} w_{j',new}}$$

(8)

In particular, we increased the weight of a given key trend ($i \in I$) by t times (Equation 6) while keeping the figures for the remaining key trends ($j \neq i, j \in I$) the same (Equation 7). Then, the relative importance of each key trend is normalized (Equation 8). $t = 1.5$ means that the weight of trend i increases by 50%, which can be considered a small change; $t = 2.0$ indicates that the weight of trend i is doubled. Thereafter, we raised the value of t incrementally by 1.0 until t_{Max}, with which the weight of the originally least important criterion, say, w_{Min}, became higher than that of the originally most vital criterion, say, w_{Max}: $t_{Max} = \min\{t' \in \mathbb{Z}: w_{Min} \times t' > w_{Max}\}$. This value of t helped us determine which LC tools consistently remained above the cutoff threshold even when the most crucial criterion changed, implying a marked shift in the evaluation focus. Details will be provided in the next section.

Research results

Key sustainable SCM trends in construction

After the third conference round, the top seven key sustainable SCM trends in construction over the forthcoming years were determined (see **Exhibit 6**), namely *SC integration* (*trend #1, 4.300*), *sustainable design* (*trend #2, 4.250*), *sustainable procurement* (*trend #3, 4.150*), *digital transformation* (*trend #4, 4.000*), *cleaner offsite logistics* (*trend #5, 3.850*), *cleaner onsite execution* (*trend #6, 3.500*), and *safety & social sustainability* (*trend #7, 2.900*). Their resultant weights are given in **Exhibit 7**.

There was a high consensus among the participant experts that SC integration (trend #1) is of paramount importance in sustainable CSCM in the upcoming years, which is in accord with the recognized importance of SC integration in CSCM (Nguyen & Le, 2022). SC integration consists of both interorganizational and intrafirm integration, incorporating parties and processes, external and internal to a focal firm (Kesidou & Sovacool, 2019). The participants stated that SC integration has been considered a critical and central approach to facilitating collaboration among SC players through mutual commitment and communication. These experts largely agreed that SC integration promotes SC members' responsibilities in sustainable construction project delivery with respect to alleviating the adverse influences of construction projects or activities on local communities and the environment.

However, to obtain sustainability, the processes integrated need to be sustainable, for instance, sustainable design (trend #2) and sustainable procurement (trend #3). Thence, with SC integration, systemwide sustainability is achieved. The experts suggested that construction designers look for sustainable materials and methods to diminish negative environmental effects and reduce energy consumption. Hence, such advanced approaches as BIM and Building Sustainability Assessment are recommended for construction design. With regard to sustainable procurement, the participants recommended governments and construction firms formulate procurement policies and practices for sustainable construction and performance improvement.

Construction sustainability also calls for cleaner offsite logistics (trend #5) and onsite execution (trend #6). The experts reached the consensus that onsite construction logistics, e.g., site layout planning and material handling, must be more productive and cleaner. A productive site layout enables material handling with smooth material and equipment flows, thus enhancing the safety and efficacy of construction project execution. Other vital tasks to make on-site execution cleaner (e.g., lowering noise levels for various surrounding receivers and taking account of safety and environmental concerns for onsite operations) need to be considered. Moreover, with the available technologies for offsite construction, the participants suggested that construction firms search for cleaner offsite construction approaches to achieving sustainability, e.g., lean methodology, supply configurations, precast scheduling, and disturbance evaluation.

Further, SC integration necessitates information management, sharing, and processing enabled by information technology utilization (Birasnav & Bienstock., 2019; Demir et al., 2022; Nguyen et al., 2021, 2022), so digital transformation, which is changing the construction sector's landscape (Le et al., 2021), is noticeably another vital trend in sustainable CSCM (trend #4). Sustainable transformation is required of the construction industry to deal with such issues as waste, safety risks, and economic challenges. Hence, the experts believe that digital transformation can improve the construction segment's current situation by pursuing such approaches as Construction 4.0. The industry should increase the application of digital technologies, especially BIM throughout project phases to improve CSC collaboration and project performance.

Unlike the other trends aforesaid, which cover certain processes in sustainable CSCM, safety and social sustainability (trend #7) are considered key tenets of sustainable construction (Goel et al., 2019). The experts emphasized that construction management must guarantee workers' health and safety while curtailing consumption and wastage of resources, materials, and energy to reduce operating and maintenance expenses. Indeed, social sustainability in this sector requires providing employees with safe working conditions and protecting their rights.

Contributions of lean techniques to sustainable SCM trends in construction

Each LC tool in sustainable CSCM trends was weighted in Round 4 of the Delphi conference. These LC techniques can be divided into four groups, namely (i) design & engineering, (ii) project planning & control, (iii) (onsite) construction execution management, and (iv) safety management, which are presented in **Exhibit 9**. As suggested by the participant experts, the practices with weight scores above *0.0300* are deemed to play important roles in the corresponding sustainable SCM trend in construction.

Exhibit 9. Weights of lean techniques that contribute to sustainable SCM trends in construction

The results show that there are 16 lean tools contributing to SC integration (*trend #1*). In the category of design & engineering, virtual design construction (VDC), design workshop (big room workshop), integrated project delivery (IPD), standardization, and concurrent engineering (CE) play vital roles in SC integration. Obviously, standardization facilitates SC members' participation and compliance throughout SC processes as required in CE (Babalola et al., 2019) and IPD (Le &

Nguyen, 2022). VDC consists of computer-based tools which support design error testing and transfer the final design to subsequent activities (Babalola et al., 2019) while big room workshops (design workshops) are to incorporate relevant stakeholders in the design phase (Le & Nguyen, 2022). These elements noticeably enable CSC integration, especially in the design phase. As to planning and control tools, last planner system (LPS), pull scheduling/planning (PS/P), and daily cluster/huddle meeting (DC/HM) are considered most crucial in attaining CSC integration. While the LPS integrates multiple types of schedules and plans, i.e., master plans, phase plans, lookahead plans, and weekly work plans (AlSehaimi et al., 2014), to augment coordination efficacy (Perez & Ghosh, 2018), DC/HM engages relevant actors for joint problem-solving (Aslam et al., 2020), and PS/P entails clients' input to initiate demand-driven operations (Ansah & Sorooshian, 2017; Aslam et al., 2020; Babalola et al., 2019). Other planning and control tools that facilitate the smooth flows of work and resources among sites from design to project delivery include work structuring & scheduling (WS&S) (Rocha et al., 2022) and location-based management system (LBMS) (Olivieri et al., 2018). With value stream mapping and benchmarking, desired targets are clearly defined and communicated (Babalola et al., 2019; Le & Nguyen, 2022; Ramani & KSD, 2019) so that CSC partners can work toward common goals, which in turn supports SC integration. Among construction and site management practices, total productive/preventive maintenance (TPM), Justin-Time (JIT), teamwork & partnering, and conference management (CM) are crucial contributors to SC integration. In effect, TPM and JIT entail integrating operational activities (Kannan & Tan, 2005). Teamwork & partnering is obviously part of SC integration while CM, which focuses on organizing workshops on operational coordination (Babalola et al., 2019), is also regarded by the participant experts as an important tool in SC integration.

Regarding trend #2 (Sustainable design), design and engineering practices are arguably deemed vital in this sustainable CSCM trend in our results. Given the importance of sustainable design in SC sustainability (Nyikos et al., 2012), the design process must engage relevant stakeholders and processes via such tools as LPS, WS&S, LBMS, PS/P, DC/HM, teamwork & partnering, JIT, and CM as discussed above. Other key tools that facilitate the smooth flows of work and resources among sites from design to project delivery include error proofing (Poka-Yoke), Gemba walk (site visits and field trips to obtain pertinent and direct insights) (Le & Nguyen, 2022), and Kaizen (continuous process improvement). A majority of these tools also play major parts in *sustainable procurement* (trend #3) and *digital transformation* (trend #4) in that construction processes in sustainable CSCM trends are interconnected and integrated. As safety conditions must be satisfied in sustainable designs (Oh et al., 2017), all health and safety management practices are considered crucial in this trend by the participants.

Likewise, all lean tools in the health and safety management category are considered by the participant experts to be vital contributors to trend #7 (Safety and social sustainability) as well as the trends related to construction execution (Cleaner offsite logistics and onsite execution). The tool contributing specifically to these trends but not to the others is 5S, which helps arrange work layout and tools safely and efficiently (Aslam et al., 2020). The other practices that contribute largely to these trends rather than to the others include first-run study, which models construction operations to examine errors and generate alternative pathways for error prevention or mitigation, and visual management, which makes information and workflows comprehensible and visible to labor and management on the shopfloor (Aslam et al., 2020; Demirkesen & Bayhan, 2020; Le & Nguyen, 2022).

We can see that the roles of these lean tools vary across the seven sustainable CSCM trends identified. To determine their overall importance in sustainable CSCM, we computed the weighted average of their relative importance over these seven key trends. Indeed, where s_{ij} denotes the relative importance score of tool i in trend j and w_j stands for trend j's weight, the weighted average score of tool i in sustainable CSCM is $\sum_{j=1}^{7} s_{ij}w_j$. Lean practices with weighted average scores above 0.030 are highlighted in **Exhibit 10**.

Exhibit 10. Ranking of lean tools' contributions to sustainable CSCM trends

Turning first to the design and engineering practices, VDC, CE, and standardization are the most crucial. Indeed, they are vital contributors to all the key sustainable CSCM trends identified in the previous rounds because they allow integrating all relevant SC processes and actors so that sustainable designs are created with holistic inputs and then transferred and executed consistently in subsequent activities. This result is in line with the extant literature in green CSCM since a firm's environmental effect is only as good as that of its suppliers (Ofori, 2000). As a result, IPD and design workshops, followed by detailed briefing and TVD, also play important roles in attaining systemwide sustainable CSCM. Modularization in construction means decomposing a built system into modules that can be manufactured offsite (prefabricated) efficiently before being transported onsite for final assembly (Rocha & Kemmer, 2018; Liu & Lu, 2018). The economic and environmental benefits of this tool (Liu & Lu, 2018; Wang et al., 2018) certainly contribute to sustainable CSCM. Design structure matrix (DSM) is only considered important in *sustainable design* (trend #2), *sustainable procurement* (trend #3), and *digital transformation* (trend #4), but it is still a key tool in sustainable CSCM because it facilitates complex system management via modeling, visualization, and analysis of interdependent entities in the system (Wen et al., 2021).

The utilization of the discussed lean tools arguably fuels the advancement of digital transformation in the construction sector to support sustainability practices (Tahmasebinia et al., 2020).

In the planning and control category, the LPS is the leading tool, playing a vital part in all the seven sustainable CSCM trends, followed by DC/HM and WS&S, respectively. As discussed above, sustainable CSCM requires incorporating various processes and actors, so planning and control tools that integrate multiple plans/schedules (LPS) and partners (DC/HM) and smooth the flows of work and resources (WS&S) are of real importance. PS/P, Poka-Yoke, and LBMS are deemed significant in fewer trends by the participant experts but remain indispensable overall because they help reduce waste.

With regard to the construction and site management practices, teamwork & partnering is the leading tool in all the seven sustainable CSCM trends in that it fulfills the need to integrate partners and processes. Contributing significantly to six of the key trends is CM for integrated operations coordination. JIT, Kaizen, and Gemba walk are important contributors to five sustainable CSCM trends. Given the nature of these construction and site management practices, it is noticeable that the key trends they support are *cleaner offsite logistics* and *onsite execution*. Moreover, all these construction and site management tools commonly contribute to *sustainable procurement* and *design* by integrating operations and enhancing efficiency.

Finally, all health and safety management practices contribute significantly to sustainable CSCM in our results. Indeed, labor health and safety in construction belong to the key tenet of the segment's social sustainability (Goel et al., 2019). These tools are considered axiomatically crucial in *safety & social sustainability* and *sustainable design*, which influence the safety of subsequent activities (Karakhan & Gambatese, 2017), including *sustainable procurement*, and *cleaner offsite logistics* and *onsite execution*.

Sensitivity analysis

Since the evaluation of lean tools in sustainable CSCM depends on the relative importance of the key trends identified as strategic criteria, we adopted the sensitivity analysis procedure of YazdaniChamzini and Yakhchali (2012), Scala and Pazour (2016), and Alamdari et al. (2022) to check the robustness of the assessment results. As previously discussed, we increased the weight of a given

key trend ($i \in I$) by $t = 1.5, 2.0, 3.0, \dots, t_{Max}$ while keeping those of the remaining key trends ($j \neq i, j \in I$) unchanged. t_{Max} is the integer with which the weight of the originally least important criterion, say, w_{Min} becomes higher than that of the originally most important criterion, say, w_{Max}: $t_{Max} \in \mathbb{Z}$: $w_{Min} \times t_{Max} > w_{Max}$. The weight of the most vital criterion, SC integration, was 2.250 times as high as that of the least important criterion. This means that any given criterion in our evaluation could become the most important when multiplied by 3.0. For further robustness, we let $t_{Max} = 4.0$.

Given four new scenarios for each of the seven key trends, we have a total of 28 (= 4 × 7) scenarios in sensitivity analysis, which are described in **Exhibit 11**. The sensitivity analysis results are depicted in **Exhibit 12**.

Exhibit 11. Notation for sensitivity analysis

Overall, small changes in the criterion weight up to 50% ($t = 1.5$) did not change the original results. When $t > 1.5$, TVD and *health & safety improvement management* (H&SIM) dropped below the cutoff threshold. Indeed, when the weight of SC integration (trend #1) increased at least twofold, the overall score of TVD fell below 0.030, whereas that of H&SIM dropped below that threshold when SC integration (trend #1) increased fourfold in its importance weight. When *digital transformation* (trend #4) increased at least threefold in its importance weight, the overall score of

H&SIM fell below the cutoff value, whereas TVD experienced a similar pattern when *cleaner onsite execution* (trend #6) increased at least three times in its importance weight. When trend #7 became the most important, TVD also hit the 0.030 threshold. Nonetheless, the other 21 tools were robustly retained despite the shifts in the weights assigned to the evaluation criteria. Therefore, we retained these 21 tools, which will be leveraged for our conceptual modeling.

Exhibit 12. Sensitivity analysis results

Among the tools that remained the ten most important LC techniques above the cutoff threshold in all scenarios, the largest proportion belonged to the category of design & engineering practices, namely VDC, design workshops (big room workshops), IPD, standardization, and CE. This result emphasizes the importance of the lean tools in this category in sustainable CSCM. In the planning and control category, LPS and DC/HM are considered robustly important lean tools in sustainable CSCM, whereas their counterpart in the construction & site management group is teamwork & partnering. Of particular note is that these tools relate closely to SC integration as discussed in the preceding subsection.

Result discussions and implications

Discussions of lean practices for sustainable CSCM

Practices for lean design & architectural engineering

Regarding the lean design & engineering practices, VDC, particularly BIM, is a top recommended tool by the experts for sustainable CSCM. This result substantiates the argument of Le and Nguyen (2022), confirming that VDC tools can boost information sharing and exchange, improve quick responses to clients' demands, and advance construction sustainability. Empirical evidence shows the support of VDC for the trends of sustainable CSCM and the improvement of sustainable performance:

- Economic dimension: VDC, a set of important digital tools, ameliorates the economic performance of sustainable construction by shortening the process of design development, diminishing rework, and improving constructability (Le & Nguyen, 2022). In terms of *sustainable design* (trend #2) and *sustainable procurement* (trend #3), VDC and other lean tools (CE, design standardization, IPD, and DW) can foster SC stakeholders' participation in the early stage of the project to increase process productivity, reduce potential risks, and improve clients' satisfaction throughout the project lifecycle (Babalola et al., 2019). For instance, CE helps CSC members create a cohesive design to decrease the time for error fixing and rework during the projects (Babalola et al., 2019). Meanwhile, IPD requires integrating key CSC actors to prevent such problems as excessive duration, over-cost, and inefficient information sharing (Roy et al., 2018). Likewise, design workshops help CSC members eliminate complications and generate original concepts for solutions in design (Babalola et al., 2019). VDC (especially BIM) facilitates *digital transformation* (trend #4) and enhances construction standardization by creating a structure of building objects with their recognized codes. These codes advance the standardization of data for building design and construction operations (Siebelink et al., 2018). In an example of digital transformation maturity, BIM-based applications can be expanded from 3D to n-D models to capture a variety of issues and respond quickly to changing customer demand. The other lean tools that the participants also recommended for architectural design & engineering practices are DSM, DB, and P&M. These tools can be applied together with VDC to increase design productivity and then facilitate efficient onsite and offsite construction operations. The results are consistent with Aslam et al. (2020), Babalola et al. (2019), and Rocha and

Kemmer (2018), who promoted these tools to boost the economic performance of building projects.

- Environmental dimension: Using lean practices (with VDC, CE, design standardization, IPD, and DW) can support CSC sustainability by reducing the reliance on fossil fuels and paperwork in construction projects (Le & Nguyen, 2022; Carvajal-Arango et al., 2019). These lean tools, particularly BIM-based techniques, can facilitate the measurement and assessment of carbon emissions at different design options. *Cleaner offsite logistics* (trend #5) and *cleaner onsite execution* (trend #6) can be advanced since these lean tools enable offsite fabrication of common modules to reduce over-ordering and waste and make offcut materials reusable or recyclable. Offsite prefabrication to supply multiple construction sites indeed helps avoid repeated setups, reduce offcut materials, and achieve scale economies. Then, common modules can fit multiple designs, so fewer deliveries are needed on site. As a result, there are lower levels of on-site transportation costs, fuel consumption, carbon emissions, and noise pollution. These results accord with the studies of Carvajal-Arango et al. (2019) and Carvalho et al. (2017), which used these tools to improve the environmental performance of construction projects.
- Social dimension: VDC, especially BIM, and other lean tools (CE, design standardization, IPD, and DW) ameliorate the social performance of CSCM by assuring health and safety in the workplace, addressing social issues of buildings, and improving collaboration among SC actors (Carvalho et al., 2017; Carvajal-Arango et al., 2019). *SC integration* (trend #1) and *digital transformation* (trend #4) are important in boosting social sustainability in the construction sector and are strongly supported by the mentioned lean tools. Based on VDC tools, visualized 3D models can be developed and assessed early by all relevant partners.

Digital and concurrent designs also ease the comparison of alternative options and the assessment of their social impacts on special interest groups and surrounding communities. BIM-based clash detections have been applied to the early stage of design to diagnose possible constructability problems before operating the building construction to guarantee safety. Hence, these recommended lean tools can be implemented to ensure worker safety and workmanship quality, which in turn translate into higher quality and greater durability of the building. The experts' recommendations are overall in accordance with Carvalho et al. (2017) and Carvajal-Arango et al. (2019).

Practices for lean project planning and control

To advance the planning and control of projects, the critical lean tool that the participant experts highly recommended is the *last planner system* (LPS). Together with other lean tools, the LPS boosts the sustainable performance of construction projects as follows:

- Economic dimension: Today's construction projects are complex, uncertain, and subject to planning changes. The LPS is considered a critical tool for project planning and control in LC as it improves planning dependability, increases construction productivity, and smooths workflows (Perez & Ghosh, 2018) by assimilating the main schedules, i.e., master plan, phase plan, look-ahead schedule, and weekly task schedule, to facilitate efficient project planning, coordination, and delivery. The experts agreed that this tool supports sustainable CSCM since it requires a commitment to reliable planning, variability reduction, and cost savings. Long- and short-term planning are connected in the LPS by applying lookahead scheduling. The LPS aims to detect possible issues and improve the applicability of project plans for construction operations. The experts also suggested other lean tools (DC/HM, WS&S, Poka-Yoke, and PS/P) to promote team problem-solving, error proofing, work variability reduction, and efficient scheduling. These results lend support to the studies of Aslam et al. (2020) and Babalola et al. (2019).

- Environmental dimension: The implementation of the LPS and other lean tools (DC/HM, WS&S, Poka-Yoke, and PS/P) can make positive impacts on the surrounding environment: decrease in energy consumption, carbon emission, waste, rework, defect, and overstock (Perez & Ghosh, 2018; Carvalho et al., 2017). The findings are in accord with the study of Le & Nguyen (2022), which suggested using these tools to plan and control projects to achieve construction sustainability.
- Social dimension: The LPS is practiced as a pull system that promotes cooperative planning and analysis of inappropriate planning. As such, the LPS increases employees' cooperation and trust during construction processes. Lookahead scheduling is applied to conduct firstrun studies, recognize constraints, allocate tasks, and manage resources and information. Hence, the LPS can focus the planning on safe working conditions, cement relationships among stakeholders, and increase employees' commitment to continuous improvement. To maximize those social benefits, the experts also recommended that the LPS be applied together with other lean techniques such as DC/HM, WS&S, Poka-Yoke, and PS/P. Similar results can be found in the studies of Carvalho et al. (2017) and Carvajal-Arango et al.

  (2019).

Practices for lean onsite execution and safety issues

Aiming to promote the sustainability of onsite construction operations, the experts recommended effective lean tools for problem-solving (T&P, CM, and GW), continuous improvement (Kaizen and JIT), and safety control (FSQ&S and PC&WE). These experts' recommendations match the findings of Babalola et al. (2019) and Le and Nguyen (2022), which confirmed the importance of these practices in onsite operations and safety control.

- Economic dimension: T&P, CM, and GW are lean practices which integrate SC members for onsite problem-solving. These tools concentrate on recognizing and assessing onsite problems and suggesting appropriate solutions to improve onsite efficiency. Meanwhile, Kaizen and JIT are the practices that focus on continuous improvement to construction processes. These techniques benefit onsite execution with productivity improvement, cost reduction, and client satisfaction (Ansah & Sorooshian, 2017; Le & Nguyen, 2022). With these tools, waste can be minimized, and unnecessary activities can be reduced. All those benefits translate into reduced cost and increased profitability.
- Environmental dimension: Using lean practices (Kaizen, FSQ&S, and PC&WE) to manage onsite execution has positive effects on the construction environment: decreased waste, better working environment, reduced carbon emissions, and sustainable innovation (Carvalho et al., 2017). These lean tools are useful for the assessment, identification, and control of problems that cause waste and negatively impact the working environment.
- Social dimension: For onsite safety management, the experts recommended two techniques (FSQ&S and PC&WE). This result is in line with research of Babalola et al. (2019) and Le and Nguyen (2022), which suggested that health and safety practices advance the safety and wellbeing for onsite workers by forecasting, assessing, and controlling possible risks as well as offering solutions to mitigate them.

Managerial implications

As mentioned above, to cope with the sustainable CSCM trends, the experts suggested VDC and LPS as strategic practices for lean *architectural engineering & design* as well as *project scheduling*

& control, respectively. The suggestion accords with previous research findings, e.g., Carvalho et al. (2017), Carvajal-Arango et al. (2019), Aslam et al. (2020), Babalola et al. (2019), and Le and Nguyen (2022). We developed a conceptual framework (see Exhibit 13) to provide managerial implications that show construction practitioners how to implement lean practices to achieve CSC sustainability.

Exhibit 13. Framework for lean practices to achieve CSC sustainability

For this framework, we follow the SC perspective, which promotes the integration of relevant SC actors to enhance project performance (Koskela et al., 2002; Le & Nguyen, 2022). Based on the above research results, we recommend the roles of relevant SC actors for three functions in a construction project (Design and architectural engineering; project planning and control; and onsite construction and safety management) as the following:

For design and architectural engineering:

- CSC driver/coordinator: For CSC coordination, the client and/or main contractor should become the CSC driver to integrate CSC members for design and architectural engineering (Nguyen & Le, 2022). As presented in **Exhibit 13**, before starting a construction project, the CSC driver should set the seven sustainable CSCM trends as the strategic targets to follow throughout the project. *VDC* can be applied as the main tool to integrate CSC players to produce efficient designs with respect to the seven trends identified. To advance design collaboration and stakeholders' trust, together with *VDC*, the CSC driver can implement these practices: *IPD, CE, or DW*. To promote other relevant CSC actors' participation in assessing potential problems, lean practices for detailed structure design (like DSM or DB) are recommended for the CSC driver. In addition, standardization and modularization of building components have significant influences on sustainable performance. The CSC driver is advised to incentivize designers and subcontractors to commit to the deployment of these two lean practices (designers applying design standardization and subcontractors applying P&M) to ameliorate building constructability and installation productivity of modular components.

- Other relevant CSC actors (designers, key suppliers, subcontractors, etc.): In effect, the architectural and engineering data need to be shared (by designers) with other stakeholders through the VDC system during this phase. The application of lean practices for design integration (e.g., *IPD, CE, or DW*) can provide the design team with additional yet pertinent inputs from stakeholders to augment design efficiency. Taking into consideration the development of detailed drawings, designers specify bills of materials (BOMs) as well as evaluate probable problems of building constructability. Together with designers, the involvement of important subcontractors and suppliers in the processes of design is also necessary to improve building constructability as well as client satisfaction as possible problems associated with materials supply and constructability may be overlooked without their participation. Consequently, waste caused by delays and reworks can increase costs and adversely impact the project schedule.

For project planning and control:

- CSC driver/coordinator: The CSC driver is responsible for mobilizing CSC stakeholders' expertise in establishing a safe and reliable workflow and providing construction teams with a master plan. The *LPS* is suggested as the principal practice for project scheduling and control since it reduces the negative impacts of process inconsistencies by advancing staff's learning and collaboration. To ameliorate project planning and control, the CSC driver is recommended to implement the LPS together with: (i) PS/P to reduce waste and leverage collaboration; (ii) PY to prevent or detect mistakes; (iii) WS&S to promote task standardization and decrease process inconsistency; or (iv) LBMS to analyze the workflow of each activity based on designated locations. Moreover, the CSC driver ought to combine DC/HM with the LPS to enhance joint problem-solving.

- Other relevant CSC actors (designers, key suppliers, subcontractors, etc.): Applying the *LPS*, project stakeholders collaboratively determine which work in each project stage must be accomplished before entering the next stage. The planner deciding at what time the next stage starts is known as the last planner. For a large project, each stage must be overseen by a last planner. Indeed, the *LPS* necessitates each construction practitioner tracking and allocating accountability during the whole workflow. The last planners must analyze: (i)

  Percent plan complete (to analyze the accomplishment percentage of weekly tasks); (ii) Tasks made ready (to explore the root causes for why fewer tasks get ready than planned); (iii) Tasks anticipated (to determine how many tasks are planned for the upcoming week).

For onsite construction and safety management:

- CSC driver/coordinator: To advance sustainable onsite construction, the CSC driver should call for relevant CSC actors' participation in continuous improvement, problem-solving, and safety control. Construction execution relies on teamwork, where each team fulfills particular tasks and then sends them to the next team(s) for subsequent steps. Henceforth, the CSC driver ought to apply *CM* or *T&P* to foster associated workers' teamwork on site. Together with these tools, *GW* can be deployed to resolve on-site problems about workers' cooperation by reporting the problems and recognizing critical reasons for "what is going wrong." Also, construction activities and on-site working conditions should be improved continuously to boost the economic, environmental, and social performance of the project.

The CSC driver can implement *Kaizen* and *JIT* separately or integratively to reduce errors and ameliorate construction site environments and processes. These practices promote continuous improvement by conducting multiple minor changes, building teamwork, and strengthening workers' commitment to their assigned tasks. To improve the social aspects of on-site operations, construction managers should apply lean practices for safety control (e.g., FSQ&S and PC&WE). If applied appropriately, these tools can keep on-site workers safe since they help predict probable risks and take mitigation measures. Safe and favorable workplaces raise productivity which in turn translates into high quality and timely delivery of the constructed building.

- Other relevant CSC actors: For this stage of the project, such relevant CSC actors as key suppliers and subcontractors follow the CSC driver's instructions for applying the lean tools concerned to prepare a safe and efficient construction site.

Conclusions

By integrating the Delphi – fuzzy AHP approaches, our paper identifies key sustainable SCM trends in construction over the forthcoming years, namely, supply chain integration, sustainable design, sustainable procurement, digital transformation, cleaner offsite logistics, cleaner onsite execution, and safety & social sustainability. Leveraging the identified trends as strategic sustainability criteria to assess and rank lean construction techniques, we recommend applying lean practices to project activities: design & architectural engineering, project planning & control, (onsite) construction execution management and onsite safety guarantee. The integrated technique utilized for this study can handle uncertainties in experts' assessments to yield robust results.

Based on the findings, this work provides managerial implications by proposing a framework for lean construction techniques to attain sustainability throughout construction project phases. The framework leverages the role of *virtual design construction* as a strategically important tool for design & architectural engineering practices. Also, the *last planner system* is promoted in the framework as a centrally critical tool for planning & control of construction projects. In addition, the framework aims at the sustainability of on-site construction execution by incorporating lean construction techniques for on-site safety warranty, problem-solving, and continuous improvement.

The ranking of lean construction tools in this work is mainly grounded on the recognized sustainable construction supply chain management trends that may differ by expert. The participants we selected were practitioners and scholars in Canada's construction industry. Despite having global experiences in project management, the experts evaluated the lean tools and the sustainable supply chain management trends in construction mostly based on the situation of Canada's construction sector. Therefore, the research results reported are more likely countryspecific and its generalizability is open to future research in other contexts, e.g., multi-country or multi-segment. Lastly, the framework for lean construction practices proposed in this paper is conceptually built on the research results, so further endeavors to validate its applicability in practical contexts are needed.

Acknowledgements

We would like to thank Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for the support of time and facilities for this study. When writing this paper, the second author received a scholarship from the Natural Sciences and Engineering Research Council of Canada (grant number CGS D3-535738-2019) for his doctoral degree.

We express our sincere gratitude to the editors and the two anonymous reviewers for their valuable comments and suggestions, which significantly enhance the paper's quality.

Disclosure statement

There is no conflict of interest with any person or organization.

Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

ORCID

Phuoc Luong Le: http://orcid.org/0000-0002-8680-8670
Duy Tan Nguyen: http://orcid.org/0000-0002-3581-0463

References

Abdirad, M., & Krishnan, K. (2021). Industry 4.0 in logistics and supply chain management: a systematic literature review. *Engineering Management Journal, 33*(3), 187–201. https://doi.org/10.1080/10429247.2020.1783935.

Abioye, S. O., Oyedele, L. O., Akanbi, L., Ajayi, A., Delgado, J. M. D., Bilal, M., & Ahmed, A. (2021). Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. *Journal of Building Engineering, 44*, Article 103299. https://doi.org/10.1016/j.jobe.2021.103299.

Akkermans, H. A., Bogerd, P., Yücesan, E., & Van Wassenhove, L. N. (2003). The impact of ERP on supply chain management: Exploratory findings from a European Delphi study. *European Journal of operational research, 146*(2), 284–301. https://doi.org/10.1016/S03772217(02)00550-7.

Alamdari, A. M., Jabarzadeh, Y., Adams, B., Samson, D., & Khanmohammadi, S. (2022). An analytic network process model to prioritize supply chain risks in green residential megaprojects. *Operations Management Research*. https://doi.org/10.1007/s12063-022-00288-

2

Al-Aomar, R. (2012). A lean construction framework with Six Sigma rating. *International Journal of Lean Six Sigma, 3*(4), 299–314. https://doi.org/10.1108/20401461211284761.

AlSehaimi, A. O., Fazenda, P. T., & Koskela, L. (2014). Improving construction management practice with the Last Planner System: a case study. *Engineering, Construction and Architectural Management*, *21*(1), 51–64. https://doi.org/10.1108/ECAM-03-2012-0032.

Amirghodsi, S., Bonyadi Naeini, A., & Roozbehani, B. (2020). An Integrated Shannon-PAF Method on Gray Numbers to Rank Technology Transfer Strategies. *Engineering Management Journal*, *32*(3), 186-207. https://doi.org/10.1080/10429247.2020.1738879.

Andersen, B., Belay, A. M., & Seim, E. A. (2012). Lean construction practices and its effects: a case at St Olav's integrated hospital, Norway. *Lean Construction Journal*. https://leanconstruction.org/uploads/wp/media/docs/lcj/2012/LCJ_12_003.pdf.

Ansah, R. H., & Sorooshian, S. (2017). Effect of lean tools to control external environment risks of construction projects. *Sustainable Cities and Society, 32*, 348–356. https://doi.org/10.1016/j.scs.2017.03.027.

Arashpour, M., Bai, Y., Aranda-Mena, G., Bab-Hadiashar, A., Hosseini, R., & Kalutara, P. (2017). Optimizing decisions in advanced manufacturing of prefabricated products: Theorizing supply chain configurations in off-site construction. *Automation in Construction, 84*, 146-153.. https://doi.org/10.1016/j.autcon.2017.08.032.

Ashenbaum, B., Blair, C. W., & Brewer, B. (2020). The influence of the competitive landscape on cross-functional interactions between procurement and engineering. *Journal of Purchasing and Supply Management*, *26*(1), Article 100595. https://doi.org/10.1016/j.pursup.2019.100595.

Aslam, M., Gao, Z., & Smith, G. (2020). Development of Innovative Integrated Last Planner System (ILPS). *International Journal of Civil Engineering*, *18*, 701–715. https://doi.org/10.1007/s40999-020-00504-9

Aslam, M., Gao, Z., & Smith, G. (2022). Framework for selection of lean construction tools based on lean objectives and functionalities. International Journal of Construction Management, 22(8), 1559–1570. https://doi.org/10.1080/15623599.2020.1729933

Athapaththu, K. I., & Karunasena, G. (2018). Framework for sustainable construction practices in Sri Lanka. *Built Environment Project and Asset Management*, *8*(1), 51–63. https://doi.org/10.1108/BEPAM-11-2016-0060.

Aziz, F. R., & Hafez. M. S. (2013). Applying lean thinking in construction and performance improvement. *Alexandria Engineering Journal*, *52*(4), 679–695. https://doi.org/10.1016/j.aej.2013.04.008.

Babalola, O., Ibem, E. O., & Ezema, I. C. (2019). Implementation of lean practices in the construction industry: A systematic review. *Building and Management*, *148*, 34-43. https://doi.org/10.1016/j.buildenv.2018.10.051.

Birasnav, M., & Bienstock, J. (2019). Supply chain integration, advanced manufacturing technology, and strategic leadership: An empirical study. *Computers & Industrial Engineering*, *130*, 142–157. https://doi.org/10.1016/j.cie.2019.01.021.

Booth, C. A., Hammond, F. N., Lamond, J., & Proverbs, D. G. (2012). *Solutions for climate change challenges in the built environment*. Blackwell: John Wiley & Sons.

Bos, A., Kemper, B., & de Waal, V. (2014). A study on how to improve the throughput time of Lean Six Sigma projects in a construction company. *International Journal of Lean Six Sigma*, *5*(2), 212–226. https://doi.org/10.1108/IJLSS-10-2013-0055.

Brammer, S., & Walker, H. (2011). Sustainable procurement in the public sector: an international comparative study. *International Journal of Operations & Production Management*, *31*(4), 452–476. https://doi.org/10.1108/01443571111119551.

Carvajal-Arango, D., Bahamón-Jaramillo, S., Aristizábal-Monsalve, P., Vásquez-Hernández, A., & Botero, L. F. B. (2019). Relationships between lean and sustainable construction: Positive impacts of lean practices over sustainability during construction phase. *Journal of Cleaner Production*, *234*, 1322–1337. https://doi.org/10.1016/j.jclepro.2019.05.216.

Carvalho, A. C. V., Granja, A. D., & Da Silva, V. G. (2017). A systematic literature review on integrative lean and sustainability synergies over a building's lifecycle. *Sustainability*, *9*(7), Article 1156. https://doi.org/10.3390/su9071156.

Carvalho, J. P., Bragança, L., & Mateus, R. (2021). Sustainable building design: Analysing the feasibility of BIM platforms to support practical building sustainability assessment. *Computers in Industry*, *127*, Article 103400. https://doi.org/10.1016/j.compind.2021.103400.

Chileshe, N., Rameezdeen, R., Hosseini, M. R., & Lehmann, S. (2015). Barriers to implementing reverse logistics in South Australian construction organisations. *Supply Chain Management: An International Journal*, *20*(2), 179–204. https://doi.org/10.1108/SCM-10-2014-0325.

Dallasega, P., & Rauch, E. (2017). Sustainable construction supply chains through synchronized production planning and control in engineer-to-order enterprises. *Sustainability*, *9*(10), Article 1888. https://doi.org/10.3390/su9101888.

Demir, S., Gunduz, M. A., Kayikci, Y., & Paksoy, T. (2022). Readiness and maturity of smart and sustainable supply chains: a model proposal. *Engineering Management Journal*. https://doi.org/10.1080/10429247.2022.2050129.

Demirkesen, S., & Bayhan, H. G. (2020). A lean implementation success model for the construction industry. *Engineering Management Journal, 32*(3), 219–239. https://doi.org/10.1080/10429247.2020.1764834.

Dobrosavljević, A., & Urošević, S. (2022). Research of the Influence of CSR Dimensions Integration in Business Processes on the Reduction of the Employee Turnover in Apparel Industry Organizations Using AHP and TOPSIS Methods. *Engineering Management Journal*, *34*(3), 394–405. https://doi.org/10.1080/10429247.2021.1940043

Elbeltagi, E., Wefki, H., Abdrabou, S., Dawood, M., & Ramzy, A. (2017). Visualized strategy for predicting buildings energy consumption during early design stage using parametric analysis. *Journal of Building Engineering*, *13*, 127–136. https://doi.org/10.1016/j.jobe.2017.07.012.

Eriksen, M. H., Bjarløv, S. P., & Rode, C. (2017). Strengthening requirement specification in sustainable procurement–An investigation of challenges. *Journal of Green Building*, *12*(1), 107–122. https://doi.org/10.3992/1552-6100.12.1.107.

Erol, H., Dikmen, I., & Birgonul, T. M. (2017). Measuring the impact of lean construction practices on project duration and variability : a simulation-based study on residential buildings. *Journal of Civil Engineering and Management*, *23*(2), 241–251. https://doi.org/10.3846/13923730.2015.1068846.

García de Soto, B., Agustí-Juan, I., Joss, S., & Hunhevicz, J. (2022). Implications of Construction 4.0 to the workforce and organizational structures. *International Journal of Construction Management*, *22*(2), 205–217. https://doi.org/10.1080/15623599.2019.1616414

Geng, S., Hou, H., & Yang, J. (2022). A Hybrid Decision Support Model for Deploying Humanitarian Operations to Respond to Earthquakes. *Engineering Management Journal*, *34*(4), 705–717. https://doi.org/10.1080/10429247.2022.2027206.

Goel, A., Ganesh, L. S., & Kaur, A. (2019). Sustainability integration in the management of construction projects: A morphological analysis of over two decades' research literature. *Journal of Cleaner Production*, *236*, Article 117676. https://doi.org/10.1016/j.jclepro.2019.117676.

Gracht, H. A. (2012). Consensus measurement in Delphi studies: review and implications for future quality assurance. *Technological Forecasting and Social Change*, *79*(8), 1525–1536. https://doi.org/10.1016/j.techfore.2012.04.013.

Gunasekara, K., Perera, S., Hardie, M., & Jin, X. (2021). A contractor-centric construction performance model using non-price measures. *Buildings*, *11*(8), Article 375. https://doi.org/10.3390/buildings11080375.

Hall, D. M., Whyte, J. K., & Lessing, J. (2020). Mirror-breaking strategies to enable digital manufacturing in Silicon Valley construction firms: a comparative case study. *Construction Management and Economics*, *38*(4), 322–339. https://doi.org/10.1080/01446193.2019.1656814.

Hammad, A. W. A., Akbarnezhad, A., & Rey, D. (2016). A multi-objective mixed integer nonlinear programming model for construction site layout planning to minimise noise pollution and transport costs. *Automation in Construction*, *61*, 73–85. https://doi.org/10.1016/j.autcon.2015.10.010.

Ho, D., Kumar, A., & Shiwakoti, N. (2019). A literature review of supply chain collaboration mechanisms and their impact on performance. *Engineering Management Journal*, *31*(1), 47-68. https://doi.org/10.1080/10429247.2019.1565625.

Holton, I., Glass, J., & Price, A. D. F. (2010). Managing for sustainability: findings from four company case studies in the UK precast concrete industry. *Journal of Cleaner Production*, *18*(2), 152–160. https://doi.org/10.1016/j.jclepro.2009.09.016.

Hosseini, M. R., Rameezdeen, R., Chileshe, N., & Lehmann, S. (2015). Reverse logistics in the construction industry. *Waste Management & Research*, *33*(6), 499–514. https://doi.org/org/10.1177/0734242X15584842.

Im, K. S., Han, S. H., Koo, B., & Jung, D. Y. (2009). Formulation of a pull production system for optimal inventory control of temporary rebar assembly plants. *Canadian Journal of Civil Engineering*, *36*(9), 1444–1458. https://doi.org/10.1139/L09-072.

Jamil, A. H., & Fathi, M. S. (2016). The integration of lean construction and sustainable construction: A stakeholder perspective in analyzing sustainable lean construction strategies in Malaysia. *Procedia Computer Science*, *100*, 634–643. https://doi.org/10.1016/j.procs.2016.09.205.

Johansen, E., & Walter, L. (2007). Lean construction: Prospects for the German construction industry. *Lean Construction Journal*, *3*(1), 19–32. https://nrl.northumbria.ac.uk/id/eprint/1746/1/LCJ_06_003.pdf.

Kannan, V. R., & Tan, K. C. (2005). Just in time, total quality management, and supply chain management: understanding their linkages and impact on business performance. *Omega*, *33*(2), 153–162. https://doi.org/10.1016/j.omega.2004.03.012.

Karakhan, A. A., & Gambatese, J. A. (2017). Integrating worker health and safety into sustainable design and construction: Designer and constructor perspectives. *Journal of Construction Engineering and Management*, *143*(9), Article 04017069. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001379.

Kesidou, S., & Sovacool, B. K. (2019). Supply chain integration for low-carbon buildings: A critical interdisciplinary review. *Renewable and Sustainable Energy Reviews*, *113*, Article 109274. https://doi.org/10.1016/j.rser.2019.109274.

Khanzadi, M., Sheikhkhoshkar, M., & Banihashemi, S. (2020). BIM applications toward key performance indicators of construction projects in Iran. *International Journal of Construction Management*, *20*(4), 305–320. https://doi.org/10.1080/15623599.2018.1484852.

Khodeir, L. M., & Othman, R. (2018). Examining the interaction between lean and sustainability principles in the management process of AEC industry. *Ain Shams Engineering Journal*, *9*(4), 1627–1634. https://doi.org/10.1016/j.asej.2016.12.005.

Kibert, C. J. (2016). *Sustainable construction: green building design and delivery*. New Jersey: John Wiley & Sons.

Kosanoglu, F., & Kus, H. T. (2021). Sustainable supply chain management in construction industry: a Turkish case. *Clean Technologies and Environmental Policy*, *23*(9), 2589–2613. https://doi.org/10.1007/s10098-021-02175-z.

Koskela, L., Howell, G., Ballard, G., & Tommelein, I. (2002). The foundations of lean construction. In R. Best & G. de Valence (Eds.), *Design and Construction: Building in Value* (1st ed., pp. 211–226). Routledge. https://doi.org/10.4324/9780080491080

Kylili, A., & Fokaides, P. A. (2017). Policy trends for the sustainability assessment of construction materials: A review. *Sustainable Cities and Society*, *35*, 280–288. https://doi.org/10.1016/j.scs.2017.08.013.

Le, P. L., & Nguyen, N. T. D. (2022). Prospect of lean practices towards construction supply chain management trends. *International Journal of Lean Six Sigma*, *13*(3), 557–593. https://doi.org/10.1108/IJLSS-06-2020-0071.

Le, P. L., Jarroudi, I., Dao, T. M., & Chaabane, A. (2021). Integrated construction supply chain: an optimal decision-making model with third-party logistics partnership. *Construction Management and Economics*, *39*(2), 133–155. https://doi.org/10.1080/01446193.2020.1831037.

Li, S., Wu, X., Zhou, Y., & Liu, X. (2017). A study on the evaluation of implementation level of lean construction in two Chinese firms. *Renewable and Sustainable Energy Reviews*, *71*, 846–851. https://doi.org/10.1016/j.rser.2016.12.112.

Liang, S. Y., Putuhena, F. J., Ling, L. P., & Baharun, A. (2014). Towards implementation and achievement of construction and environmental quality in the Malaysian construction industry. *Malaysian Journal of Civil Engineering*, *26*(1), 99–114. https://doi.org/10.11113/mjce.v26.15879.

Linstone, H. A., & Turoff, M. (1975). *The Delphi Method, Techniques and Applications*. London: Addison-Wesley Reading.

Liu, J., & Lu, M. (2018). Constraint programming approach to optimizing project schedules under material logistics and crew availability constraints. *Journal of Construction Engineering and Management*, *144*(7), Article 04018049. https://doi.org/10.1061/(ASCE)CO.19437862.0001507.

Liu, Z., Chen, K., Peh, L., & Tan, K. W. (2017). A feasibility study of building information modeling for green mark new non-residential building (NRB): 2015 analysis. *Energy Procedia*, *143*, 80–87. https://doi.org/10.1016/j.egypro.2017.12.651.

Maltese, S., Tagliabue, L. C., Cecconi, F. R., Pasini, D., Manfren, M., & Ciribini, A. L. C. (2017). Sustainability assessment through green BIM for environmental, social and economic efficiency. *Procedia Engineering*, *180*, 520–530. https://doi.org/10.1016/j.proeng.2017.04.211.

Mangla, S. K., Kumar, P., & Barua, M. K. (2015). Risk analysis in green supply chain using fuzzy AHP approach: A case study. *Resources, Conservation and Recycling*, *104*, 375–390. https://doi.org/10.1016/j.resconrec.2015.01.001

Meehan, J., & Bryde, D. J. (2015). A field-level examination of the adoption of sustainable procurement in the social housing sector. *International Journal of Operations & Production Management*, *35*(7), 982–1004. https://doi.org/10.1108/IJOPM-07-2014-0359.

Mofidi, A., Tompa, E., Mortazavi, S. B., Esfahanipour, A., & Demers, P. A. (2020). A probabilistic approach for economic evaluation of occupational health and safety interventions: a case study of silica exposure reduction interventions in the construction sector. *BMC Public Health*, *20*(1), Article 210. https://doi.org/10.1186/s12889-020-8307-7.

Muhammad, W. M. N. W., Ismail, Z., & Hashim, A. E. (2013). Exploring lean construction components for Malaysian construction industry. Paper presented at the *2013 IEEE Business Engineering and Industrial Applications Colloquium (BEIAC)*, Langkawi, Malaysia, April 7-9. https://ieeexplore.ieee.org/document/6560091.

Newaz, M. T., Ershadi, M., Jefferies, M., & Davis, P. (2021). Assessing safety management factors to develop a research agenda for the construction industry. *Safety Science*, *142*, Article 105396. https://doi.org/10.1016/j.ssci.2021.105396.

Nguyen, D. T., & Le, P. L. (2022). Twenty-year application of logistics and supply chain management in the construction industry. *Construction Management and Economics*, *40*(10), 796–834. https://doi.org/ 10.1080/01446193.2022.2110273

Nguyen, D. T., Adulyasak, Y., & Landry, S. (2021). Research manuscript: The Bullwhip Effect in rule-based supply chain planning systems–A case-based simulation at a hard goods retailer. *Omega*, *98*, Article 102121. https://doi.org/10.1016/j.omega.2019.102121

Nguyen, D. T., Adulyasak, Y., Cordeau, J.-F., & Ponce, S. I. (2022). Data-driven operations and supply chain management: established research clusters from 2000 to early 2020. *International Journal of Production Research*, *60*(17), 5407–5431. https://doi.org/10.1080/00207543.2021.1956695

Ning, X., Ding, L. Y., Luo, H. B., & Qi, S. J. (2016). A multi-attribute model for construction site layout using intuitionistic fuzzy logic. *Automation in Construction*, *72*, 380–387. https://doi.org/10.1016/j.autcon.2016.09.008.

Ning, X., Lam, K.-C., & Lam, M. C.-K. (2010). Dynamic construction site layout planning using max-min ant system. *Automation in Construction*, *19*(1), 55–65. https://doi.org/10.1016/j.autcon.2009.09.002.

Nyikos, D. M., Thal, A. E., Hicks, M. J., & Leach, S. E. (2012). To LEED or not to LEED: Analysis of cost premiums associated with sustainable facility design. *Engineering Management Journal, 24*(4), 50-62. https://doi.org/10.1080/10429247.2012.11431955.

Ofori, G. (2000). Greening the construction supply chain in Singapore. *European Journal of Purchasing and Supply Management*, *6*(3), 195–206. https://doi.org/10.1016/S09697012(00)00015-0.

Ogunbiyi, O. (2014). *Implementation of the Lean Approach in Sustainable Construction: a Conceptual Framework*. Doctoral thesis, University of Central Lancashire, UK. http://clok.uclan.ac.uk/10563.

Oh, B. K., Choi, S. W., & Park, H. S. (2017). Influence of variations in CO2 emission data upon environmental impact of building construction. *Journal of Cleaner Production*, *140*, 1194–1203. https://doi.org/10.1016/j.jclepro.2016.10.041.

Okudan, O., Budayan, C., & Dikmen, I. (2021). A knowledge-based risk management tool for construction projects using case-based reasoning. *Expert Systems with Applications*, *173*, Article 114776. https://doi.org/10.1016/j.eswa.2021.114776.

Olivieri, H., Seppänen, O., & Granja, A. D. (2018). Improving workflow and resource usage in construction schedules through location-based management system (LBMS). *Construction Management and Economics*, *36*(2), 109–124. https://doi.org/10.1080/01446193.2017.1410561.

Perez, A. M., & Ghosh, S. (2018). Barriers faced by new-adopter of Last Planner System: a case study. *Engineering, Construction and Architectural Management*, *25*(9), 1110–1126. https://doi.org/10.1108/ECAM-08-2017-0162.

Pitt, M., Tucker, M., Riley, M., & Longden, J. (2009). Towards sustainable construction: promotion and best practices. *Construction Innovation*, *9*(2), 201–224. https://doi.org/10.1108/14714170910950830.

Rahimi, M., & Ghezavati, V. (2018). Sustainable multi-period reverse logistics network design and plan- ning under uncertainty utilizing conditional value at risk (CVaR) for recycling construction and demolition waste. *Journal of Cleaner Production*, *172*, 1567–1581. https://doi.org/10.1016/j.jclepro.2017.10.240.

Rahman, A. H., Wang, C., & Lim, I. Y. W. (2012). Waste processing framework for non-valueadding activities using lean construction. *Journal of Frontiers in Construction Management*, *1*(1), 8–13. http://www.academicpub.org/fce/paperInfo.aspx?ID=3

Ramani, P. V., & KSD., L. K. L. (2021). Application of lean in construction using value stream mapping. *Engineering, Construction and Architectural Management*, *28*(1), 216–228. https://doi.org/10.1108/ECAM-12-2018-0572.

Rameezdeen, R., Chileshe, N., Hosseini, M. R., & Lehmann, S. (2016). A qualitative examination of major barriers in implementation of reverse logistics within the South Australian construction sector. *International Journal of Construction Management*, *16*(3), 185–196. https://doi.org/10.1080/15623599.2015.1110275.

Ramkumar, M., & Jenamani, M. (2015). Sustainability in supply chain through e-procurement—An assessment framework based on DANP and liberatore score. *IEEE Systems Journal*, *9*(4), 1554–1564. https://doi.org/10.1109/JSYST.2014.2336291.

Rayens, M. K., & Hahn, E. J. (2000). Building consensus using the policy Delphi method. *Policy, Politics, and Nursing Practice*, *1*(4), 308–315. https://doi.org/10.1177/152715440000100409.

Rocha, C. G., & Kemmer, S. (2018). Integrating product and process design in construction. *Construction Management and Economics*, *36*(9), 535–543. https://doi.org/10.1080/01446193.2018.1464198

Rocha, C. G., Korb, S., & Sacks, R. (2022). Work structuring and product design for customized repetitive projects. *Construction Management and Economics*, *40*(7-8), 526–547. https://doi.org/10.1080/01446193.2021.1936100

Roy, D., Malsane, S., & Samanta, P. K. (2018). Identification of Critical Challenges for Adoption of Integrated Project Delivery. *Lean Construction Journal*, 1–15. https://leanconstruction.org/uploads/wp/media/docs/lcj/2018/LCJ_17_007.pdf.

Rybkowski, Z. K., Arroyo, P., & Parrish, K. (2022). Assessment of current target value design practices: consistencies and inconsistencies of application. *Construction Management and Economics*, *40*(7-8), 598–617. https://doi.org/10.1080/01446193.2022.2037146

Saaty, T. L. (1980). *The Analytic Hierarchy Process*. New York: McGraw-Hill.

Salem, O., Solomon, J., Genaidy, A., & Luegring, M. (2005). Site implementation and assessment of lean. *Lean Construction Journal*, *2*(2), 1–21.

https://leanconstruction.org/uploads/wp/media/docs/lcj/V2_N2/LCJ_05_009.pdf.

Salvatirerra, J. L., Alarcon, L. F., Lopez, A., & Valasquez, X. (2015). Lean diagnosis for Chilean construction industry: towards more sustainable lean practices. Paper presented at *23rd Annual Conference of the International Groups for Lean Construction*, Perth, Australia, July 29-31, 642-651.

Sarhan, J. G., Fawzia, S., & Karim, A. (2017). Lean construction implementation in the Saudi arabian construction industry. *Construction Economics and Building*, *17*(1), 46–69. https://doi.org/10.5130/AJCEB.v17i1.5098.

Sarhan, S., Pasquire, C., Elnokaly, A., & Pretlove, S. (2019). Lean and Sustainable Construction: A Systematic Critical Review of 25 Years of IGLC Research. *Lean Construction Journal*, 1–20. https://leanconstruction.org/uploads/wp/media/docs/lcj/2019/LCJ_19_004.pdf.

Scala, N. M., & Pazour, J. A. (2016). A Value Model for Asset Tracking Technology to Support Naval Sea-Based Resupply. *Engineering Management Journal*, *28*(2), 120–130. https://doi.org/10.1080/10429247.2016.1168502

Seppanem, O., Modrich, R., & Ballard, G. (2015). Integration of last planner system and location based management system. Paper presented at *23rd Annual Conference of the International Groups for Lean Construction*, Perth, Australia, July 29-31, 123-132.

Shouke, C., Zhuobin, W., & Jie, L. (2010). Comprehensive evaluation for construction performance in concurrent engineering environment. *International Journal of Project Management*, *28*(7), 708–718. https://doi.org/10.1016/j.ijproman.2009.11.004.

Siebelink, S., Voordijk, J. T., & Adriaanse, A. (2018). Developing and testing a tool to evaluate BIM maturity: sectoral analysis in the Dutch construction industry. *Journal of Construction Engineering and Management*, *144*(8), Article 05018007. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001527.

Singh, A., Kumari, S., Malekpoor, H., & Mishra, N. (2018). Big data cloud computing framework for low carbon supplier selection in the beef supply chain. *Journal of Cleaner Production*, *202*, 139–149. https://doi.org/10.1016/j.jclepro.2018.07.236.

Solaimani, S., & Sedighi, M. (2020). Toward a holistic view on lean sustainable construction: A literature review. *Journal of Cleaner Production*, *248*, Article 119213. https://doi.org/10.1016/j.jclepro.2019.119213.

Tahmasebinia, F., Sepasgozar, S. M. E., Shirowzhan, S., Niemela, M., Tripp, A., Nagabhyrava, S., Mansuri, K. K. Z., & Alonso-Marroquin, F. (2020). Criteria development for sustainable construction manufacturing in Construction Industry 4.0. *Construction Innovation*, *20*(3), 379–400. https://doi.org/10.1108/CI-10-2019-0103.

Tamošaitienė, J., Sarvari, H., Cristofaro, M., & Chan, D. W. M. (2021). Identifying and Prioritizing the Selection Criteria of Appropriate Repair and Maintenance Methods for Commercial Buildings. *International Journal of Strategic Property Management*, *25*(5), 413–431. https://doi.org/10.3846/ijspm.2021.15225.

Tan, Y., Shen, L., & Yao, H. (2011). Sustainable construction practice and contractors' competitiveness: A preliminary study. *Habitat international*, *35*(2), 225–230. https://doi.org/10.1016/j.habitatint.2010.09.008.

Thyssen, M. H., Emmitt, S., Bonke, S., & Kirk-Christoffersen, A. (2010). Facilitating client value creation in the conceptual design phase of construction projects: a workshop approach. *Architectural Engineering and Design Management*, *6*(1), 18–30. https://doi.org/10.3763/aedm.2008.0095.

Tsai, F. M., Bui, T. D., Tseng, M. L., Ali, M. H., Lim, M. K., & Chiu, A. S. (2021). Sustainable supply chain management trends in world regions: A data-driven analysis. *Resources, Conservation and Recycling*, *167*, Article 105421.

https://doi.org/10.1016/j.resconrec.2021.105421.

Tsao, C. C. Y., Tommelein, I. D., Swanlund, E. S., & Howell, G. A. (2004). Work structuring to achieve integrated product-process design. *Journal of Construction Engineering and Management*, *130*(6), 180–189. https://doi.org/10.1061/(ASCE)0733-9364(2004)130:6(780).

Verrier, B., Rose, B., & Caillaud, E. (2015). Lean and Green strategy: the Lean and Green House and maturity deployment model. *Journal of Cleaner Production*, *116*, 150–156. https://doi.org/10.1016/j.jclepro.2015.12.022.

Wang, Z., Hu, H., & Gong, J. (2018). Simulation based multiple disturbances evaluation in the precast supply chain for improved disturbance prevention. *Journal of Cleaner Production*, *177*, 232–244. https://doi.org/10.1016/j.jclepro.2017.12.188.

Wen, M., Lin, J., Qian, Y., & Huang, W. (2021). Scheduling interrelated activities in complex projects under high-order rework: A DSM-based approach. *Computers & Operations Research*, *130*, Article 105246. https://doi.org/10.1016/j.cor.2021.105246.

Wernicke, B., Stehn, L., Sezer, A. A., & Thunberg, M. (2021). Introduction of a digital maturity assessment framework for construction site operations. *International Journal of Construction Management*. https://doi.org/10.1080/15623599.2021.1943629.

Whyte, J. (2019). How digital information transforms project delivery models. *Project Management Journal*, *50*(2), 177–194. https://doi.org/10.1177/8756972818823304.

Yazdani-Chamzini, A., & Yakhchali, S. H. (2012). Tunnel Boring Machine (TBM) selection using fuzzy multicriteria decision making methods. *Tunnelling and Underground Space Technology*, *30*, 194–204. https://doi.org/10.1016/j.tust.2012.02.021.

Yu, A. T. W., Yevu, S. K., & Nani, G. (2020). Towards an integration framework for promoting electronic procurement and sustainable procurement in the construction industry: A systematic literature review. *Journal of Cleaner Production*, *250*, Article 119493. https://doi.org/10.1016/j.jclepro.2019.119493.

Zeng, N., Liu, Y., Mao, C., & König, M. (2018). Investigating the relationship between construction supply chain integration and sustainable use of material: Evidence from China. *Sustainability*, *10*(10), Article 3581. https://doi.org/10.3390/su10103581.

About the Authors

Phuoc-Luong Le, PhD, is a Lecturer of Operations Management at School of Industrial Management, Ho Chi Minh City University of Technology (HCMUT), Vietnam National University (VNU-HCM). He holds a PhD degree in Supply Chain Engineering and Management at ÉTS, University of Québec, Montréal, Canada. His research interest focuses on supply chain management, lean manufacturing, operations, and production management.

Duy-Tan Nguyen is a PhD candidate in Logistics and Operations Management at HEC Montréal and a student member of the Group for *Research* in Decision Analysis (GERAD), Montréal, Canada. His research focus is on inventory control, distribution planning, and supply chain management.

Contact: Phuoc-Luong Le, Department of Production and Operations Management, School of Industrial Management, Ho Chi Minh City University of Technology (HCMUT), Vietnam National University Ho Chi Minh City (VNU-HCM), 268 Ly Thuong Kiet, District 10, Ho Chi Minh City, Vietnam; lpluong@hcmut.edu.vn.

Exhibit 1. Review of trends in sustainable CSCM.

Trends in sustainable CSCM	Authors
Standards and guidelines for sustainable construction	Kylili and Fokaides (2017); Athapaththu and Karunasena (2018)
Measurements and reporting for sustainable construction	Holton et al. (2010); Pitt et al. (2009); Athapaththu and Karunasena (2018)); Tan et al. (2011)
SC integration for sustainable construction	Carvalho et al. (2021); Le and Nguyen (2022); Zeng et al. (2018); Kosanoglu and Kus (2021); Le et al. (2021)
Sustainable construction design	Elbeltagi et al. (2017); Liu et al. (2017); Maltese et al. (2017)
Digital transformation for sustainable construction	Whyte (2019); Abioye et al. (2021); Wernicke et al. (2021); García de Soto et al. (2022); Hall et al. (2020)
Sustainable construction procurement	Brammer and Walker (2011); Yu et al. (2020); Meehan and Bryde (2015); Eriksen et al. (2017)
Education and training for sustainable construction	Tan et al. (2011); Liang et al. (2014); Athapaththu and Karunasena (2018)
Process innovations for sustainable construction	Liang et al. (2014); Athapaththu and Karunasena (2018); Booth et al. (2012)
Cleaner offsite construction logistics	Arashpour et al. (2017); Im et al. (2009); Liu and Lu (2018); Wang et al. (2018)
Cleaner onsite construction execution	Hammad et al. (2016); Ning *et al.* (2010); Ning et al. (2016); Le et al. (2021)
Reverse logistics for sustainable construction	Chileshe et al. (2015); Rameezdeen et al. (2016); Rahimi and Ghezavati (2018); Hosseini et al. (2015)
Safety and social sustainability	Dallasega and Rauch (2017); Solaimani and Sedighi (2020); Kosanoglu and Kus (2021); Tsai et al. (2021)
Risk management for sustainable construction	Mofidi et al. (2020); Newaz et al. (2021); Okudan et al. (2021).

Exhibit 2. Review of the utmost applied tools for practices of LC

Lean construction tools ***A B C D E F G H I J K L M N O P Q R***

Practices for design and engineering

1 VDC (Virtual design construction) x x x x x x x x 2 DSM (Design structure matrix) x x x x x 3 P&M (Prefabrication & modularization) x x x x x 4 DB (Detailed briefing) x x x x
5 DW (Design workshops) x x x x x 6 IPD (Integrated project delivery) x x x x x 7 TVD (Target value design) x x x x 8 Standardization x x x x x x x
9 CE (Concurrent engineering) x x x x x x x x x 10 CPA (Construction process analysis) x x x 11 TP (Team preparation) x x x x 12 SG (Smart goal) x x
13 Jidoka x x x **Practices for planning and control**

1 LPS (Last planner system) x x
x x x
x x x x
x x
x x

2 WS&S (Work structuring & scheduling) x
x x

x
x x x

LBMS (Location-based management
3 x x
x x x
system)

4 Benchmarking x

x x x
5 VSM (Value stream mapping) x x x x x x
x x x 6 DC/HM (Daily cluster or huddle meeting)
x x x x x x x x x x x 7 PS/P (Pull
scheduling/planning) x x x x x x x
8 PY (Poka-Yoke) x x
x x x
9 BNA (Bottleneck analysis) x x x 10 LB (Line balancing) x x x x 11 CF (Continuous flow) x x
x x x 12 MPH (Multi-process handling) x x
13 FIFO line x x x

Practices for onsite management

1 GW (Gemba or Muda walk) x x x x x x 2 TPM (Total productive maintenance) x x x x x x x x 3 KS/PS (Kanban system or pull system) x x x x x x x
4 5S x x x x x x
x x x
5 FRS (First run study) x x x x x x x x 6 Kaizen x x x x x x x
7 T&P (Teamwork & partnering) x x x x x x x x 8 JIT (Just-in-time) x x x x x x x x x x x x x
9 VM (Visual management) x x x x x x x x x x x x x 10 CM (Conference management) x x x x x 11 QFD (Quality function deployment) x x x x x 12 PDCA (Plan-do-check-act) x x x 13 SPC (Statistical process control) x x
x 14 7BT (7 basic tools) x x x x 15 5 whys x x x x x
16 FMEA (Failure mode & effects analysis) x x x 17 T&MS (Time & motion study) x x 18 SS (Suggestion scheme)
x x 19 SR (Setup reduction) x x x
20 CP&CP (Check points & control points) x x x

Practices for health and safety management

1 FSQ&S (Fail safe for quality & safety) x x x
x x x x PC&WE (Plan of conditions & work
2 environment) x x x x
x x x

H&SIM (Health & safety improvement
3 management) x x
x x x

Note: **A =** ***Tsao et al. (2004); B = Salem et al. (2005); C = Johansen & Walter (2007); D = Rahman et al. (2012); E = Al-Aomar (2012); F = Andersen et al. (2012); G = Muhammad et al. (2013); H = Aziz and Hafez (2013); I = Ogunbiyi (2014); J = Seppanem et al. (2015); K = Salvatirerra et al. (2015); L = Erol et al. (2017); M = Ansah and Sorooshian (2017); N = Sarhan et al. (2017); O = Li et al. (2017); P = Babalola et al. (2019); Q = Aslam et al. (2020,2022); R = Le & Nguyen (2022).***

Exhibit 3. Summary of methodological steps

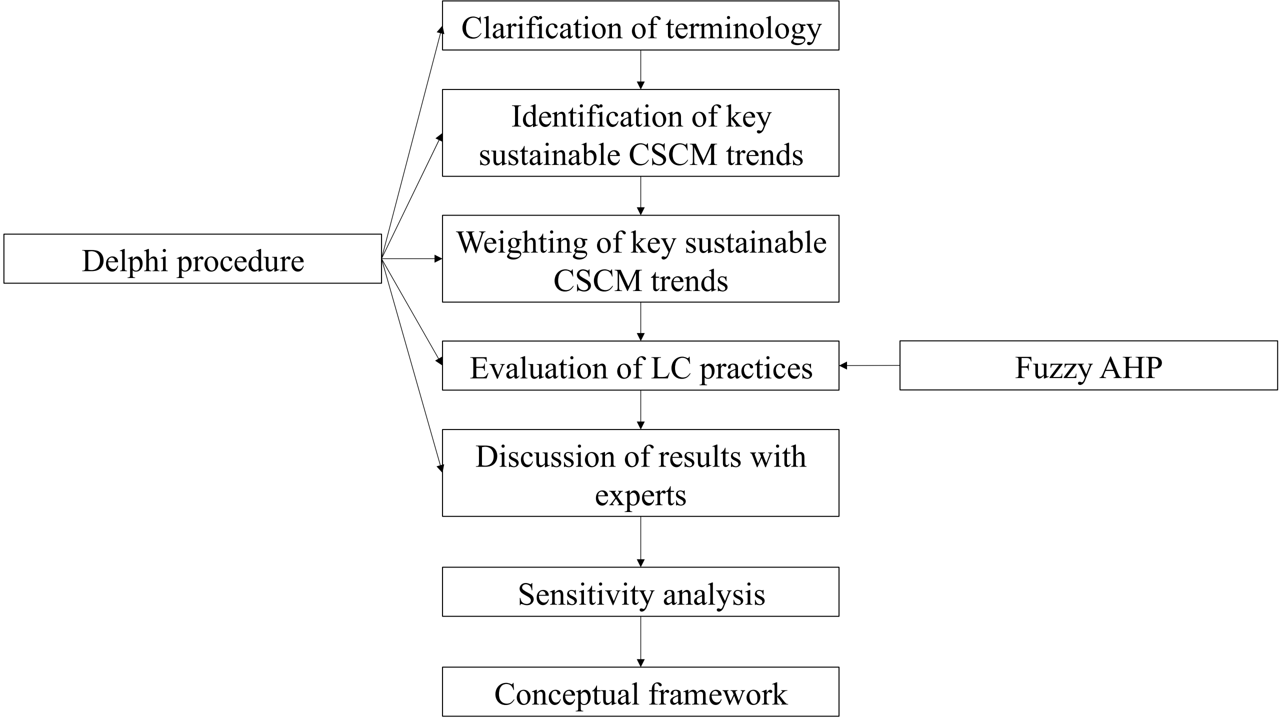
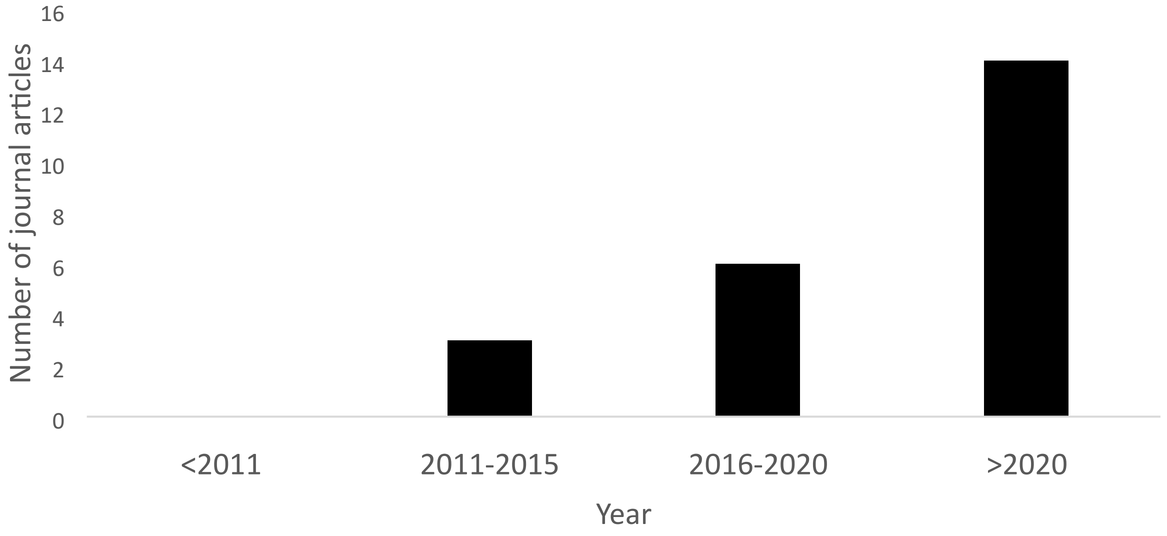


Exhibit 4. Participants' backgrounds

Position	**Number of participants**	**Average number of years of experience**	**Specialization**
Professors	5	10	LC & sustainable SCM
Researchers (PhD candidates & Postdocs)	3	5	LC & sustainable SCM
Project managers	8	9	Project management using LC tools
Architectural engineers & designers	5	7	Design & architectural engineering using LC tools
Site engineers	7	12	Site engineering using LC tools

Exhibit 5. Combined Delphi – fuzzy AHP in research on construction management



Note: Data taken from the Web of Science on 27 September 2022. Using the keywords below, we obtained 28 search results for journal articles, of which 23 papers combined the Delphi method with fuzzy AHP.

	Topic	"construction" OR "civil engineering"
And	Topic	"Delphi"
And	Topic	"fuzzy AHP" OR "fuzzy analytic hierarchy process" OR "FAHP" OR "F-AHP"
And	Language	English

Exhibit 6. Assessment of sustainable SCM trends in construction

Trends	**Descriptions**	**Mean**	**IQD**	**Removed**
1. ***SC integration for sustainable construction***	The integration of all relevant SC actors	***4.300***	***1.000***	No
2. ***Sustainable design***	The use of green designs along with sustainable resources and materials and minimized waste.	***4.250***	***0.500***	No
3. ***Sustainable procurement***	The insertion of environmental protection, societal progress, and economic development in procurement processes.	***4.150***	***0.500***	No
4. ***Digital transformation***	The use of advances in digital technologies to promote sustainable construction.	***4.000***	***1.000***	No
5. ***Cleaner offsite logistics***	Cleaner offsite prefabrication and modular construction approaches	***3.850***	***0.000***	No
6. ***Cleaner onsite execution***	Cleaner site layout planning and material handling for onsite operations	***3.500***	***0.500***	No
7. ***Safety and social sustainability***	Focusing on working conditions, employee rights, social missions, diversity and equality, health, and safety	***2.900***	***0.500***	No

8.	Reverse logistics	Effective approaches for successful reverse construction logistics	2.450	0.000	Yes
9.	Sustainable standards	Sustainable policies to ensure that the construction development meets the sustainability requirements.	2.350	0.000	Yes
10.	Process innovations	Achieving a higher sustainable level of construction processes through the innovation of sustainable technologies applied for process improvement	2.350	0.500	Yes
11.	Education and training	More commitment to sustainability through the improvement of staff education and training for projects	2.300	0.000	Yes
12.	Sustainable measurements	Adopting measurement and reporting or applying current benchmarking to appraise and improve economic, environmental, and social performance	2.300	0.000	Yes
13.	Risk management	Efficient response strategies for risk management to achieve sustainability	2.300	1.000	Yes

Exhibit 7. The AHP structure for analysis in this work

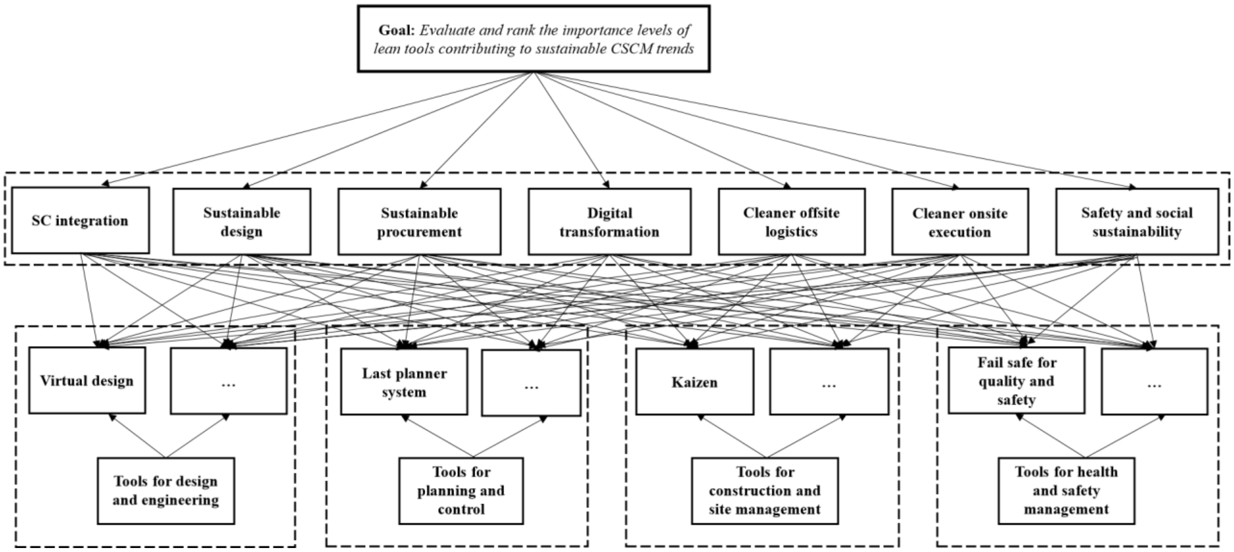


Exhibit 8. Weighting and ranking sustainable SCM trends in construction

Trend	**Weight**	**Ranking**
SC integration	0.2093	1
Sustainable design	0.1628	2
Sustainable procurement	0.1628	3
Digital transformation	0.1395	4
Cleaner offsite logistics	0.1163	5
Cleaner onsite execution	0.1163	6
Safety and social sustainability *CI = 0.030, CR = 0.015*	0.0930	7

Exhibit 9. Weights of lean techniques that contribute to sustainable SCM trends in construction

		Sustainable SCM trends in construction							
Category	**Lean tools**	***SC integration*** **(0.2093)**	***Sustainable design*** **(0.1628)**	***Sustainable procurement*** **(0.1628)**	***Digital transformation*** **(0.1395)**	***Cleaner offsite logistics*** **(0.1163)**	***Cleaner onsite execution*** **(0.1163)**	***Safety and social sustainability*** **(0.0930)**	***Overall weight*** **(1.0000)**
Design & engineering practices	Virtual Design construction (VDC)	0.0422	0.0573	0.0395	0.0516	0.0355	0.0321	0.0378	**0.0432**
	Design structure matrix (DSM)	0.0285	0.0522	0.0303	0.0421	0.0280	0.0241	0.0264	**0.0338**
	Prefabrication & modularization (P&M)	0.0285	0.0332	0.0303	0.0298	0.0496	0.0321	0.0264	**0.0324**
	Detailed briefing (DB)	0.0245	0.0488	0.0303	0.0460	0.0319	0.0241	0.0304	**0.0338**
	Design workshops (DW)/big room workshop	0.0422	0.0522	0.0477	0.0421	0.0319	0.0241	0.0304	**0.0403**
	Integrated project delivery (IPD)	0.0470	0.0522	0.0517	0.0298	0.0355	0.0283	0.0264	**0.0408**
	Target value design (TVD)	0.0245	0.0488	0.0303	0.0298	0.0280	0.0241	0.0264	**0.0307**
	Standardization	0.0390	0.0488	0.0351	0.0421	0.0451	0.0418	0.0414	**0.0416**
	Concurrent engineering (CE)	0.0422	0.0488	0.0517	0.0340	0.0420	0.0389	0.0378	**0.0429**
Planning & control practices	Last planner system (LPS)	0.0422	0.0488	0.0575	0.0460	0.0451	0.0389	0.0378	**0.0458**
	Work structuring & scheduling (WS&S)	0.0322	0.0375	0.0303	0.0421	0.0451	0.0321	0.0414	**0.0365**
	Location-based management system (LBMS)	0.0322	0.0332	0.0351	0.0298	0.0280	0.0283	0.0264	**0.0310**
	Benchmarking	0.0322	0.0086	0.0032	0.0251	0.0280	0.0241	0.0221	0.0203
	Value stream mapping (VSM)	0.0322	0.0086	0.0303	0.0298	0.0280	0.0283	0.0264	0.0262

	Daily cluster or huddle meeting (DC/HM)	0.0422	0.0375	0.0477	0.0421	0.0355	0.0283	0.0378	**0.0395**
	Pull scheduling or planning (PS/P)	0.0422	0.0332	0.0351	0.0298	0.0319	0.0241	0.0221	**0.0327**
	Poka-yoke (PY, Error proofing)	0.0285	0.0332	0.0303	0.0421	0.0355	0.0283	0.0414	**0.0334**
Construction & site management practices	Gemba walk (GW)	0.0285	0.0332	0.0303	0.0251	0.0355	0.0418	0.0378	**0.0323**
	Total productive maintenance (TPM)	0.0390	0.0086	0.0303	0.0251	0.0280	0.0283	0.0304	0.0274
	Kanban system	0.0285	0.0086	0.0032	0.0000	0.0055	0.0283	0.0221	0.0139
	5S	0.0245	0.0086	0.0032	0.0251	0.0319	0.0418	0.0414	0.0230
	First run study (FRS)	0.0245	0.0086	0.0303	0.0251	0.0319	0.0418	0.0378	0.0271
	Kaizen	0.0285	0.0375	0.0303	0.0421	0.0355	0.0418	0.0264	**0.0343**
	Teamwork & partnering (T&P)	0.0422	0.0375	0.0477	0.0421	0.0355	0.0418	0.0414	**0.0414**
	Just-in-Time (JIT)	0.0322	0.0332	0.0517	0.0251	0.0319	0.0389	0.0221	**0.0344**
	Visual management (VM)	0.0245	0.0086	0.0303	0.0298	0.0319	0.0418	0.0414	0.0280
	Conference management (CM)	0.0390	0.0332	0.0351	0.0298	0.0319	0.0389	0.0378	**0.0352**
Health & safety management practices	Fail safe for quality & safety (FSQ&S)	0.0285	0.0332	0.0303	0.0421	0.0319	0.0418	0.0467	**0.0351**
	Plan of conditions & work environment (PC&WE)	0.0285	0.0332	0.0303	0.0298	0.0319	0.0389	0.0378	**0.0322**
	Health & safety improvement management (H&SIM)	0.0285	0.0332	0.0303	0.0251	0.0319	0.0321	0.0378	**0.0308**
	Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	CR	0.002	0.006	0.002	0.001	0.003	0.002	0.000	

Exhibit 10. Ranking of lean tools’ contributions to sustainable CSCM trends

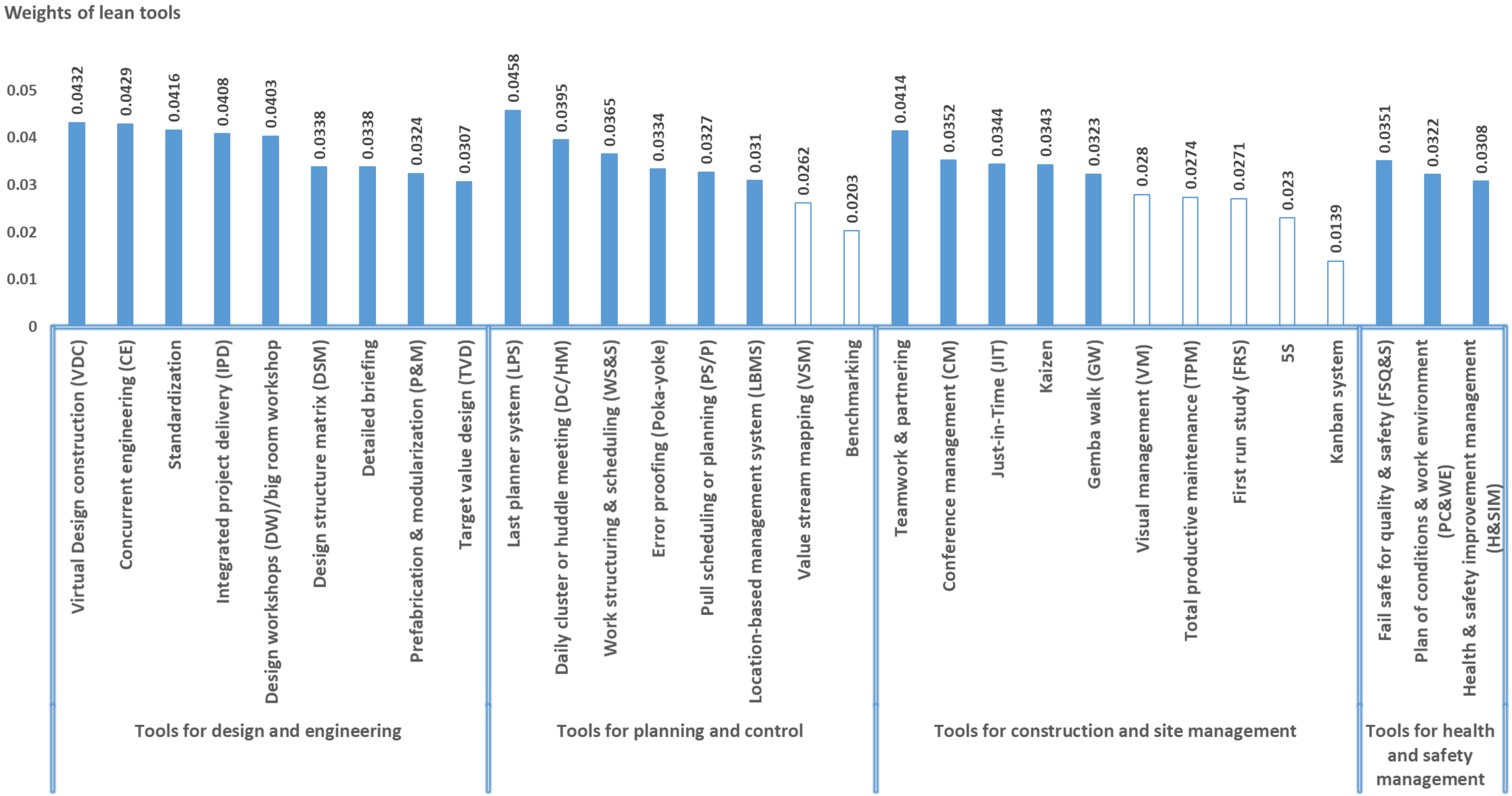
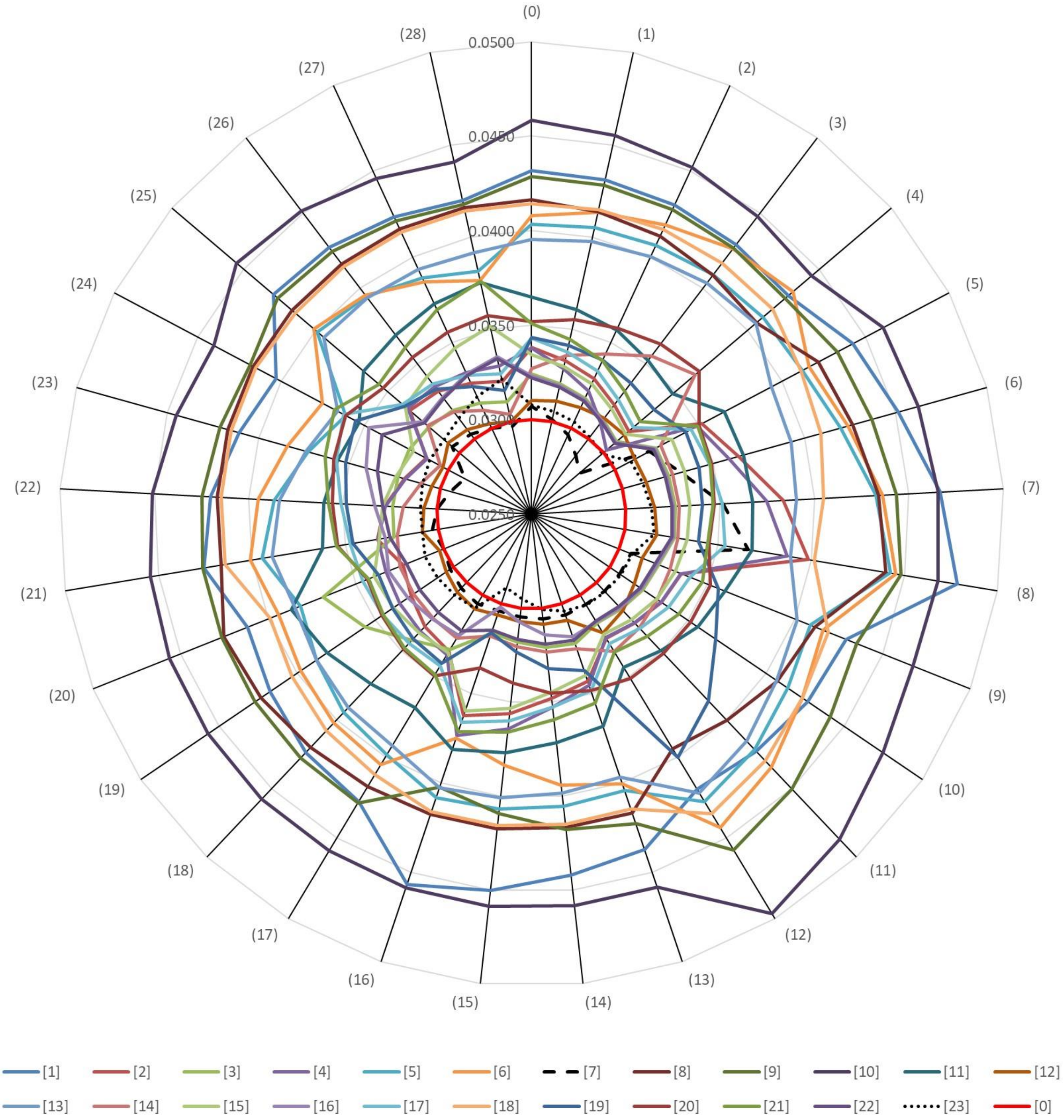


Exhibit 11 Notation for sensitivity analysis

Scenario		Lean construction tool	
(0)	Original scenario	[0]	Cutoff threshold
(1)	SC integration x 1.5	[1]	Virtual design construction (VDC)
(2)	SC integration x 2.0	[2]	Design structure matrix (DSM)
(3	SC integration x 3.0	[3]	Prefabrication & modularization (P&M)
(4)	SC integration x 4.0	[4]	Detailed briefing (DB)
(5)	Sustainable design x 1.5	[5]	Design workshops (DW)/big room workshop
(6)	Sustainable design x 2.0	[6]	Integrated project delivery (IPD)
(7)	Sustainable design x 3.0	[7]	Target value design (TVD)
(8)	Sustainable design x 4.0	[8]	Standardization
(9)	Sustainable procurement x 1.5	[9]	Concurrent engineering (CE)
(10)	Sustainable procurement x 2.0	[10]	Last planner system (LPS)
(11)	Sustainable procurement x 3.0	[11]	Work structuring & scheduling (WS&S)
(12)	Sustainable procurement x 4.0	[12]	Location-based management system (LBMS)
(13)	Digital transformation x 1.5	[13]	Daily cluster or huddle meeting (DC/HM)
(14)	Digital transformation x 2.0	[14]	Pull scheduling/planning (PS/P)
(15)	Digital transformation x 3.0	[15]	Poka-yoke (PY, Error proofing)
(16)	Digital transformation x 4.0	[16]	Gemba walk (GW)
(17)	Cleaner offsite logistics x 1.5	[17]	Kaizen
(18)	Cleaner offsite logistics x 2.0	[18]	Teamwork & partnering (T&P)
(19)	Cleaner offsite logistics x 3.0	[19]	Just-in-time (JIT)
(20)	Cleaner offsite logistics x 4.0	[20]	Conference Management (CM)
(21)	Cleaner onsite execution x 1.5	[21]	Fail safe for quality & safety (FSQ&S)
(22)	Cleaner onsite execution x 2.0	[22]	Plan of conditions & work environment (PC&WE)
(23)	Cleaner onsite execution x 3.0	[23]	Health & safety improvement management (H&SIM)
(24)	Cleaner onsite execution x 4.0		
(25)	Safety and social sustainability x 1.5		
(26)	Safety and social sustainability x 2.0		
(27)	Safety and social sustainability x 3.0		
(28)	Safety and social sustainability x 4.0		

Exhibit 12 Sensitivity analysis results


(0)
(1)
(2)
(3)
(4)
(5)
(6)
(7)
(8)
(9)
(10)
(11)
(12)
(13)
(14)
(15)
(16)
(17)
(18)
(19)
(20)
(21)
(22)
(23)
(24)
(25)
(26)
(27)
(28)
0.0500
0.0450
0.0400
0.0350
0.0300
0.0250
[1]
[2]
[3]
[4]
[5]
[6]
[7]
[8]
[9]
[10]
[11]
[12]
[13]
[14]
[15]
[16]
[17]
[18]
[19]
[20]
[21]
[22]
[23]
[0]

.

Note: Refer to **Exhibit 11** for explained notation.

Exhibit 13 Framework for lean practices to achieve CSC sustainability