Sarhan, S., Pasquire, C., Elnokaly, A., and Pretlove, S. (2019) Lean and Sustainable Construction: A Systematic Critical Review of 25 Years of Experience. *Lean Construction Journal* 2019 pp 01-20 (submitted 25Mar2019; Accepted 5Apr2019)
www.leanconstructionjournal.org

Lean and Sustainable Construction: A Systematic Critical Review of 25 Years of IGLC Research

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Abstract

Questions: Are there connections and trade-offs between Lean Construction (LC) and Sustainable Construction (SC)? If so, what is needed to support their integration in theory and practice? What are the gaps in knowledge and the opportunities for bringing closer linkage between research and practice?

Purpose: A growing body of knowledge has been emerging from the International Group for Lean Construction (IGLC) community, in relation to synergies between LC and Sustainability. The purpose of this study, therefore, is to critically review the progress made towards integrating LC and SC in theory and practice, in order to provide a conceptual consolidation of this knowledge.

Research Method: A Systematic Literature Review (SLR) of 'LC and Sustainability' studies published in proceedings of the IGLC annual conferences over the past 25 years, using a qualitative approach to research synthesis.

Findings: This study presents the main synergies and inconsistencies between LC and SC, reveals the main limitations in approaches to LC and SC, exposes potential enablers for integrating LC and SC, and divulges opportunities for further research

Limitations: This SLR study only includes peer-reviewed papers published by the IGLC and excludes the wider construction literature.

Implications: The findings of this study advance the research agenda providing the potential to develop sustainable improvements in practice.

Keywords: Lean Construction; Sustainability; Green; Value; Waste; Systematic Review
Paper type: Full Paper

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Introduction

The construction industry is a significant growth industry on a global level and is a fundamental part of the economy in many parts of the world. The 'Construction 2025' industrial strategy report published by the UK Government forecasts the global construction market to grow by up to 70% between 2013 and 2025 (HM Government, 2013). However, the construction sector is known to be one of the largest environmental polluters, physical waste producers, and energy consumers throughout its lifecycle (Huovila and Koskela, 1998; Oyedele *et al.*, 2013; Weinheimer *et al.*, 2017). Due to these challenges in our built environment, including issues relating to rapid growing populations and anthropogenic climate changes, there is a significant need in advancing the industry towards sustainable development. The concept of sustainable development was first coined in the Brundtland Commission, which was set up by the United Nations, as an initiative to improve the global environmental, economic and social conditions (WCED, 1987). Sustainable Construction (SC) is the response of the construction sector to the challenge of sustainable development (Huovila and Koskela, 1998). SC could be defined as "*the creation and operation of a healthy built environment based on resource-efficiency and ecological principles*" (Kibert (2005, p.2). According to Kibert (1994), while the traditional approach to construction project management focuses on cost, time and quality objectives, 'sustainability in architecture and construction' expands on these criteria to include minimisation of environmental degradation, minimisation of resource depletion, contextual, social and cultural considerations and creating a healthy built environment (Elnokaly and Vyas, 2014).

At the same time, the construction industry is also frequently criticised for its inherent inefficiencies, confrontational relationships, and low rates of productivity and profit margins, in comparison to other industries (for example see, Egan, 1998; Koskela, 2000; Sarhan *et al.*, 2017). Lean construction (LC) has been shown to be effective in helping to solve many of the industry's problems and to maximise value to the customer, through helping us to understand, identify and eliminate many of the causes and sources of (process and physical) waste in the end-to-end design and construction process (Koskela, 2000; Koskela *et al.*, 2013; Sarhan *et al.*, 2018). There is no commonly agreed definition of LC, but it is mostly attributed to the application of the Transformation-Flow-Value generation (T-F-V) theory of production to the construction environment (see Koskela 2000). The flow dimension of the theory (F) reveals the interdependency of tasks across the whole project process (Sarhan *et al.*, 2018), and thus introduces the reduction of waste as an objective of production management; whilst value generation (V) brings the customer into the focus (Koskela *et al.*, 2010). The construction sector typically recognises clients and more recently stakeholders and users, but the term 'customer' is not commonly used (Sarhan *et al.*, 2018). In this sense, a 'customer' in LC principles could include any of the aforementioned, including the concept of next customer in the production process (see Leong and Tilley, 2008), which aims to improve integration and information flow between project suppliers; thereby reducing waste and driving behaviour towards the final product and end user value.

For these reasons, it has been argued that LC has the potential to contribute towards helping the industry to meet the challenges of sustainable development. To the best of the authors' knowledge, it is Huovila and Koskela's (1998) work that first, at least within the IGLC community, put forward the proposition that sustainability in construction can

effectively be promoted and supported through LC principles. According to them, the principles of LC converge to the sustainability objectives in two main ways. First, through the focus on the concept of waste-reduction, LC can also reduce pollution, material and energy wastes during construction and maintenance. Secondly, through the concept of 'value', LC could be useful to clients aiming for both business and environmental and social excellence simultaneously.

Since 1998, a growing body of knowledge has been emerging from the LC community, in relation to synergies between LC and SC. From a production management perspective, it has been suggested by Koskela *et al*. (2010) that LC is an innovation in production theory, and that SC could be regarded as an innovation in product requirements. The link between them has also been increasingly recognised and implemented in practice. Furthermore, the concepts, tools and techniques of LC and SC themselves have been under constant refinement. The aim of this study, therefore, is to review the progress made in understanding the linkages and inconsistencies between the two approaches, by conducting a critical systematic literature review (SLR) and synthesising the findings of 'LC and Sustainability' papers published in IGLC conference proceedings. SLRs are valuable for presenting knowledge that is unlikely to be obtained from an isolated review of individual studies (Higgins and Green, 2009). By using this method, the content is analysed to establish connections, highlight gaps, explain possible discrepancies, and synthesise the findings of relevant research published by the IGLC (1993 to 2017). Following this introduction, the study will be divided into four parts. The next section presents the research problem. Subsequently, the methodological approach of the study is described, followed by an overall summary of the research findings and analysis. Finally, the conclusions are provided.

Research Problem and Context

The relation and interaction between lean and sustainability in construction has been subject to some attention and efforts from both scholars and practitioners. Both initiatives seek to reduce waste and maximise value, but through different approaches and perspectives. The sustainability agenda has largely focused on environmental issues through the reduction of emissions and energy consumption, reduced waste of materials, reduced use of non-sustainable materials and so on. These reductions are largely achieved through the application of metrics to score performance such as BREEAM and LEED. This is quite different to the lean approach which changes the socio-technical systems used to create processes that reduce all forms of resource waste (labour, materials, energy etc.) by changed relationships and practices within the design and delivery itself. These approaches include Integrated Project Delivery, Target Value Delivery, Last Planner® System for example, as well as more manufacturing lead techniques such as 5S, visual management and so on. These two views are conceptually quite different but it is a common mistake that attempts at integration form around tool focused frameworks rather than altered perceptions and understandings. The study reported here seeks to explicitly analyse these current perceptions contained within the body of literature of the IGLC.

Research methodology and objectives

This study adopted a systematic literature review (SLR) and a qualitative approach to research synthesis, following the protocols recommended by Siddawy (2014) and Mellow *et al*. (2017). This method is used to establish a critical conceptual consolidation across a growing but fragmented body of knowledge, regarding the integration of LC and SC in theory and practice.

An analytical review systematically appraises the contribution of a given body of literature (Crossan and Apaydin, 2010). In contrast to an expert (traditional) review using ad hoc literature selection describing observed features subject to unconscious bias, an SLR improves the quality of the review process and outcome by employing a methodologically rigorous and transparent approach for the entire research process (Kitchenham *et al*., 2009), in order to reduce bias and enable future replication (Mallet *et al*., 2012). An SLR reveals deeper, previously unobserved features.

SLRs originated and have been widely used in medical research since the 1970s to examine the effectiveness of health-care interventions and to promote the use of evidence-based practices in medicine, nursing and health care (Mallet *et al*., 2012). An SLR collects, critically evaluates and synthesises the findings of all relevant, high-quality individual studies that fit pre-specified eligibility criteria, to address one or more research questions and provide a comprehensive and reliable overview of the subject under investigation (Carvalho *et al*. 2017; Siddawy *et al*., 2019). Thus, a systematic review is considered a high form of evidence (Higgins and Green, 2009; Haddaway and Watson, 2016). The conclusions drawn from SLRs can contribute to the formation of a research consensus on the best form of action to be taken and hence support evidence-informed policy and practice (Thomas and Harden, 2008). According to Siddawy (2014, p.1):

> *"A systematic review is therefore a piece of research in its own right and, by its nature, is able to address much broader questions than single empirical studies ever can. Indeed, systematic reviews sit above all other research designs at the top of the 'hierarchy of evidence' because they have the potential to provide the most important practical implications".*

An SLR usually relies on the use of databases that contain a large set of research publications as well as effective search mechanisms. Typically, the planning process for an SLR consists of the following steps:

- Search method content
- Inclusion and exclusion criteria tables
- Search outcome

This study used the search engine provided by the IGLC website (available at: http://iglc.net/Papers), to search for 'LC and Sustainability' peer-reviewed papers published in IGLC conferences over the past 25 years. The IGLC database was selected, as this conference represents the state-of-the-art of LC research and practices from all around the world (Jacobs, 2010; Koladiya, 2017). The keywords used for the search query and the search outcomes are summarised in Table 1.

Table 1: Search queries and outcomes

Keywords	No. of papers matching search queries
▪ Sustainability	43
▪ Sustainable	43
▪ Sustainable + Development	6
▪ Green	31
▪ Environmental	42
▪ Energy	23

Interestingly, only 43 papers, out of all conference papers published by IGLC (around 1400 papers) over the past 25 years, were found to match the various search queries conducted. This proportion represents about 3% of all papers published in proceedings of the IGLC annual conferences from 1993 to 2017. Out of these, two papers were excluded based on title screening followed by an abstract review, due to their irrelevance. Thus, as a result of these efforts, 41 papers out of all IGLC papers over a span of 25 years were found to be relevant and thus thoroughly reviewed and analysed in this study.

The study used a deductive-inductive approach for data analysis (Figure 1), utilising QSR NVivo 11 software, and following a "*lean coding*" procedure (Creswell, 2007, p.152). As opposed to purely inductive coding approaches where researchers usually struggle to reduce the numerous lists of generated codes to the five or six main categories or themes that they must end up with for most publications; in lean coding, the researcher starts by developing a short list of five or six themes with shorthand codes, and then continues to expand and refine their coding structure as they proceed with reviewing their databases (Creswell, 2007). Accordingly, during the data coding and analysis of the 41 papers selected for the SLR (see Appendix 1), the study focused on identifying, critically evaluating, and generating the overall picture related to the following six themes:

1. Synergies between LC and SC
2. Trade-offs or inconsistencies
3. Limitations in approaches to LC
4. Limitations in approaches to SC
5. Potential enablers for the integration of LC and SC
6. Opportunities for future work

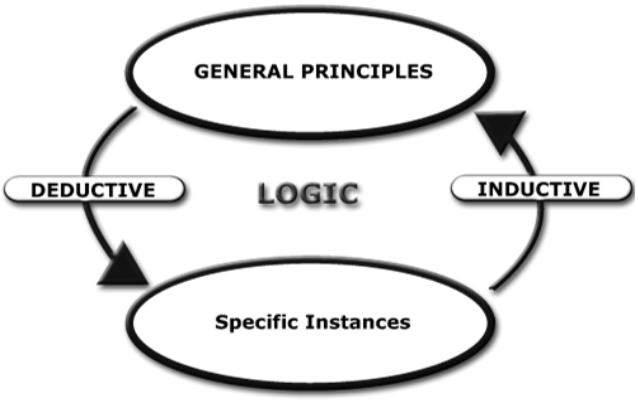

Figure 1: Data coding and analysis approach

Under each of these themes, initial codes from the SLR sample were generated, followed by axial coding leading to the development of subcategories and categories (Strauss and Corbin, 1998). Overall, the methodology of this study is that of a systematic review. It uses systematic data collection procedures, deductive-inductive data analysis and coding techniques, and theoretically grounded synthesis using Nvivo 11 as a computer-assisted qualitative data analysis software.

Results and Analysis

This section summarises the main findings of the SLR and qualitative data analysis conducted for this study.

Sample analysis

The analysis of the SLR sample enabled the study to gain an overview about:

- Frequency of studies over time
- Countries that are leading and focussing on the research topic; and
- Research methods and approaches used.

Frequency of studies over the 25 years span

As shown in Figure 2 below, studies on the integration of LC and sustainability started in 1998 with the work of Huovila and Koskela (1998). Surprisingly, no further work on the topic was explored until 2002 except for one study conducted in Brazil by Degani and Cardoso (2002) promoting the concept of 'Clean Construction'. Then, IGLC publications on the topic remained stagnant until 2005, where only one study was conducted in the USA by Luo *et al*. (2005) to explore how benefits of LC approaches to prefabrication can impact green project goals. Studies on the topic started blooming from 2011 and peaked in 2012 where seven studies were published in that year. Interest in the topic continued until 2016, but momentum dropped in 2017 with only 2 papers concentrating on the topic, out of 111 published papers (IGLC-25 in Greece). These findings reveal the slow uptake and limited amount of current research on the topic of 'LC and sustainability' within the IGLC community, despite the various theoretical and empirical supports for the synergies and benefits of their integration (see for example, Lapinski *et al*., 2006; Koskela *et al*., 2010; Nahmens and Ikuma, 2012; Ogunbiyi *et al*., 2014; Carvalho *et al*., 2017).

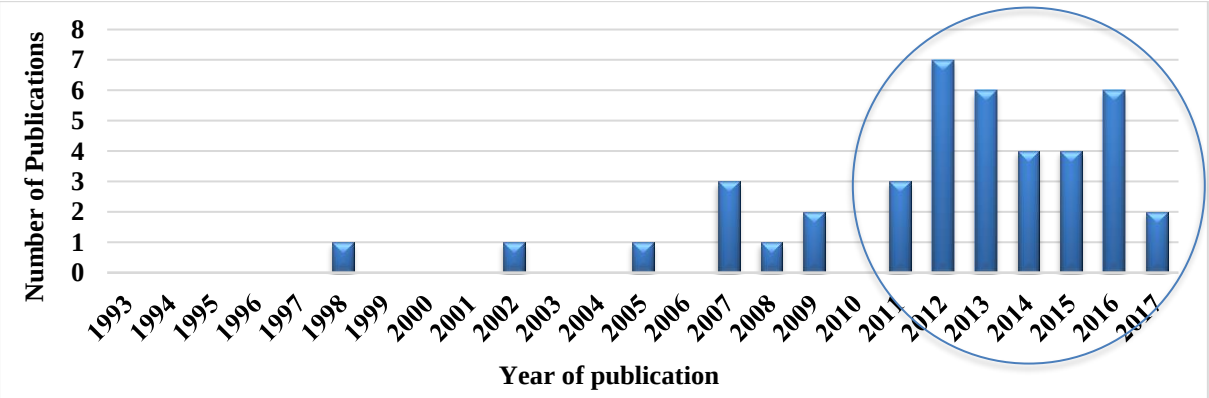

Figure 2: Number of LC-Sustainability studies per year between 1993 and 2017

Geographical distribution of studies over the 25 years span

The geographical distribution of studies scopes across 14 different countries (Figure 3), with USA and Brazil leading the way with 22 publications out of 41 (representing around 54% of the total SLR sample).

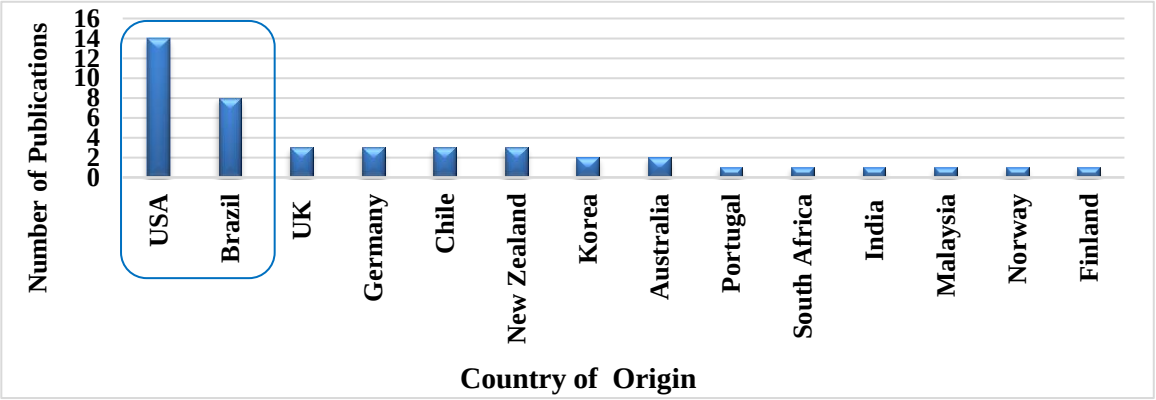

Figure 3: Geographical distribution of LC-Sustainability studies between 1993 and 2017

Research methodologies and approaches used

The SLR enabled the study to identify a number of varied methods used within the IGLC studies investigated (Figure 4). The results revealed that 'case-study' is the methodology mostly used (41%) reflecting the practice-oriented nature dominating IGLC research. These findings suggest that IGLC research has possibly responded to widespread criticisms related to the extensive use of quantitative methods, associated with positivism, in mainstream construction management research (Seymour *et al.*, 1997; Koskela, 2017). At the same time, the SLR also identified four research purposes and approaches utilised in the studies (Figure 5), following the classifications defined by Wu and Wang (2016):

- ***Conceptual Investigation*** - discusses the theoretical development of lean and sustainability (Focus is on developing theory)
- ***Theoretical* Integration** – discusses the feasibility and benefits of integrating lean and green, and possibly other techniques (Focus is on application, e.g. tools and processes)
- ***Practical Investigation*** - investigates the potential of using lean and sustainability to address specific industry problems
- ***Empirical implementation*** - investigates the implementation and quantifies the results of the implementation

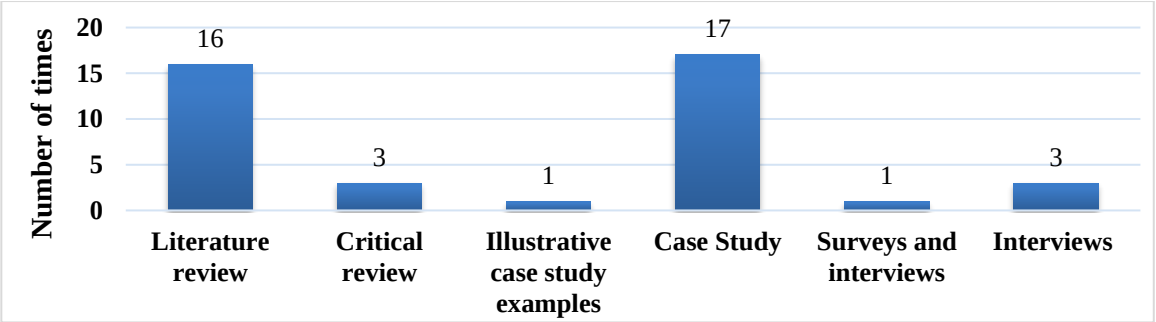

Figure 4: Research methodologies used for topics investigating LC-Sustainability

The results revealed that nearly two thirds of the studies were exploratory in nature, either conceptually or practically investigating the links between LC and sustainability. Furthermore, only 10% of all studies were carried out to implement and empirically quantify the results of the implementation. The first empirical implementation study was carried out in 2008, and no similar studies were conducted again until 2014. These findings clearly indicate that the integration of LC and sustainability is a topic that is still poorly researched and applied within the IGLC community. This is a growing field and much more evidence-based research work is hence needed to bring research closer to decision-making in both policy and practice.

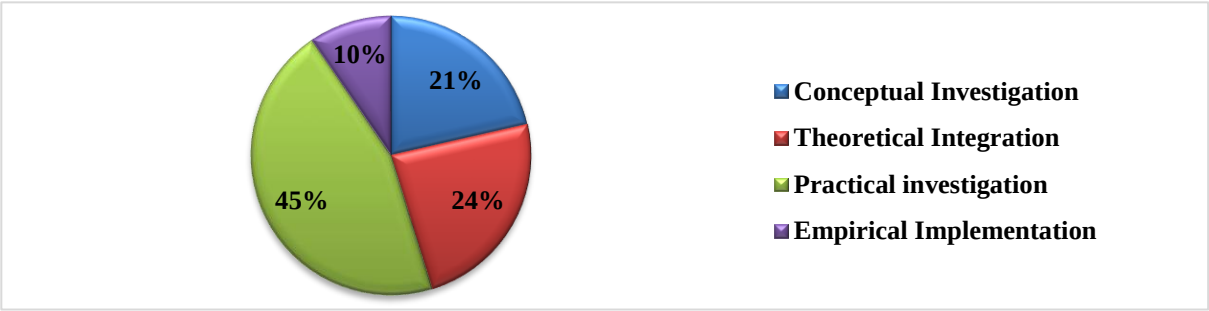

Figure 5: Research purposes and approaches

Synergies and Trade-offs between LC and SC

There is a common agreement amongst most scholars, if not all, that 'waste-reduction' and 'value-maximisation' are the most obvious connections between the two initiatives. The main difference, however, rests on the types and dimensions of 'waste' and 'value' that each initiative focuses on addressing. Lean construction is focussed on reducing both material and process wastes and maximising value at a project level; while sustainable construction gives more attention to reducing material and environmental wastes and looks at value from a global perspective. The use of an SLR has, however, enabled this study to consolidate the findings of previous studies, and thus present a more comprehensive list of commonalities and inconsistencies between LC and SC approaches, as illustrated in Figure 6.

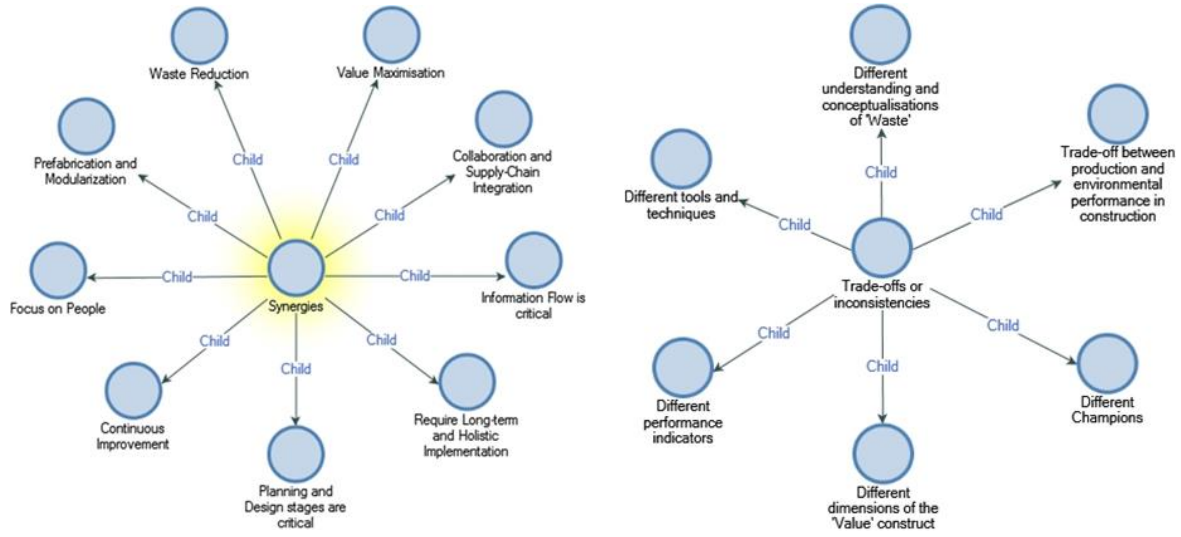

Figure 6: Synergies and trade-offs between LC and SC as emerged from SLR analysis

Limitations in approaches to LC research and practice

The study qualitatively synthesised how the reviewed studies highlighted limitations in approaches to LC as well as the suggestions they provided for theoretical integration. A summary of results is shown in Table 2.

Table 2: Limitations in approaches to LC as generated from the SLR analysis

Author(s) and Year	Categories and Subcategories
▪ Bae and Kim (2007) ▪ Carneiro et al. (2012) ▪ Huovila and Koskela (1998) ▪ Maia et al. (2011) ▪ Maris and Parrish (2016) ▪ Novak (2012) ▪ Salvatierra-Garrido and Pasquire (2011)	**Predominance of a 'limited' customer-focused perspective of 'Value'** ▪ Value delivery is limited to a 'project' rather than a 'global' perspective ▪ Main focus of lean construction is on client satisfaction and not necessarily the wider society and environmental performance ▪ Notion of customer needs to be expanded to include 'all' stakeholders ▪ The focus of value is on the end product based on clients' needs, which may not consider environmental impacts ▪ Value generation must be considered in relation to the external environment and social problems ▪ The notion of value is mostly focussed on waste-reduction rather than value-creation ▪ Notion of customer needs to be expanded to include the 'Environment'
▪ Arroyo and Gonzalez (2016) ▪ Bae and Kim (2007) ▪ Huovila and Koskela (1998) ▪ Parrish and Whelton (2013) ▪ Ramkrishnan et al. (2007) ▪ Weinheimer et al. (2017)	**Little focus and attention paid to the management of the project life cycle requirements (e.g. facilities, operations and maintenance)** ▪ Most studies focus on reducing wastes and costs at the construction stage only; only a very few take a whole project-life cycle perspective
▪ Arroyo and Gonzalez (2016); ▪ Bae and Kim (2007); ▪ Bae and Kim (2008); ▪ Belayutham and Gonzalez (2015); ▪ Salvatierra-Garrido and Pasquire (2011) ▪ Vieira and Cachadinha (2011)	**The prevailing conceptualisation of 'Waste', which does not account for environmental and social impacts** ▪ The need for a wider understanding of 'Waste' that should consider sustainability. ▪ Traditionally limited in literature to Ohno's 7 wastes (i.e. TIMWOOD) ▪ Most studies focus on assessing LC methods from an economic perspective only

Limitations in approaches to sustainable construction

The analysis of this study led to the generation of two overarching limitations in approaches to 'sustainability in architecture and construction', as illustrated in Table 3.

Table 3: Limitations in approaches to SC as evolved from the SLR analysis

Author(s) and Year	Categories and Subcategories
▪ Arroyo and Gonzalez (2016) ▪ Holloway and Parrish (2013) ▪ Johnsen and Drevland (2016) ▪ Novak (2012) ▪ Weinheimer (2016	**The over-reliance on formal 'Green Performance Certifications' (e.g. BREEAM and LEED), which limits opportunities for sustainability improvement** ▪ Building in a sustainable manner should be pursued whether or not an environmental performance (e.g. BREEAM or LEED) certification is desired ▪ LEED certifications as a barrier to sustainability goals outside its frameworks ▪ Paying less attention to social and economic aspects of sustainability ▪ Strictly following a criteria catalogue choosing cheapest options or the line of least effort does not lead to sustainability at large. ▪ The current small number of Green Buildings does not realistically help in reducing the greenhouse effect ▪ Focus during certification process is often on achieving credit points, rather than on adding value to the building and developing a useful concept for it. ▪ BREEAM or LEED lead to extra documentation, causing delays and thus productivity losses
▪ Bae and Kim (2007) ▪ Carneiro et al. (2012) ▪ Holloway and Parrish (2013) ▪ Koskela and Tommelein (2009) ▪ Maris and Parish (2016) ▪ Parrish (2012) ▪ Rosenbaum et al. (2012) ▪ Weinheimer (2016	**Much of the approaches to SC are based on the assumption, in the economic theory of production, of 'fixed input-output relations'** ▪ Main focus is on design and operational stages of projects, but much less attention is given to production delivery stage. ▪ Tools and methods used for assessing sustainability impacts of designs/materials in buildings overlook the means and management of production delivery. ▪ Sustainable design mainly focusses on health, comfort and wellbeing of occupants and the community, but gives less attention to accident-reduction and safety of workers during construction. ▪ Focusses on reducing environmental wastes but less attention to process wastes ▪ The need for new cost paradigms that consider sustainability 'value', rather than simply 'costs'. ▪ Overlooking the significance of contracts and project delivery systems as 'means to an end' ▪ Sustainability valuations often overlook or fail to account for differences in installation and operational time and quality ▪ Use of 'Prescribed Specifications' in Sustainable Design as opposed to 'Performance Specifications' in Lean Design ▪ Reliance on the use of 'Green outcome-based' performance measures, as opposed to 'process' performance measures in LC ▪ Without an efficient project management and delivery system, a waste of resources in all possible forms can result, which is not in conformity with the principles of sustainability

Potential enablers for integrating LC and SC

The analysis of the SLR conducted in this study led to the identification of various factors that have the potential to enable the integration of LC and SC approaches (Table 4). Valente *et al*. (2013) describe three different levels of a project at which companies can use LC principles and practices to complement and assist SC, and vice-versa. The first is the 'strategic level', which involves defining the construction business need and strategy and project conception. The second is the 'tactical level', which includes design development and project management. The third is the 'operational level' which covers all activities related to the construction site and facility management.

The analysis of this study led to the generation of seven fundamental enablers for integrating LC and SC at the strategic level: (1) A focus on health, safety and welfare of workers and end users; (2) A wider visualisation of value from an early stage of projects; (3) An understanding of overall life cycle costs and savings; (4) Employee training and education; (5) Recognition of the importance and commitment to corporate social responsibility; (6) The quest for continuous improvement; and (7) Commitment of owners to the sustainability agenda. At the tactical level, three enablers for integration emerged out of the analysis: (1) Integrated design and project delivery methods; (2) BIM-enabled projects; and (3) Waste-reduction strategies through design and procurement. While, at the operational level three main enablers for integrating LC and SC were developed out of the analysis: (1) Waste minimisation and management during construction and post-construction stages (e.g. Using Last Planner System as a collaborative planning technique); (2) Deploying the role of the Lean Architectural Technologist (AT); and (3) Visual management and transparency to support information flow.

Table 4: Enablers for integrating LC and SC, as generated from the SLR analysis

Author(s) and Year	Categories and Subcategories
▪ Huovila and Koskela (1998) ▪ Bae and Kim (2007) ▪ Emuze and Smallwood (2013) ▪ Carneiro *et al*. (2012) ▪ Vasconcelos *et al*. (2013) ▪ Salem et al. (2014) ▪ Arroyo and Gonzalez (2016) ▪ Johnsen and Drevland (2016) ▪ Weinheimer *et al*. (2017)	**A focus on Health, Safety and Wellbeing** ▪ Accidents as social wastes ▪ Unhealthy and unsafe practices as environmental concerns ▪ Expanding the scope from efficiency to sustainability ▪ Safe workplace, people's health, loyalty among stakeholders and improvement of the external image as social values ▪ Creating a healthy built environment ▪ Improving safety ▪ Stopping production whenever it feels unsafe ▪ Environmental wastes have H&S implications for construction workers and the general public
▪ Bae and Kim (2007) ▪ Maia *et al*. (2011) ▪ Salvatierra-Garrido and Pasquire (2011) ▪ Novak (2012) ▪ Emuze and Smallwood (2013)	**A global visualisation of value from an early stage of projects** ▪ Sustainability as an added value to clients ▪ Paradigm shift to sustainable prosperity through resource renewal and value generation ▪ Sustainability as a First Value delivery of current construction sector strategies. ▪ Sustainable practices as an integral part of the social domain of Value

▪ Gomez *et al*. (2015)	▪ Generating value at pre-construction stage ▪ Continuum of value paradigm from project to sustainability ▪ The focus on the construct of value to drive the holistic synergy between H&S, lean construction and sustainability
▪ Luo *et al*. (2005) ▪ Bae and Kim (2007) ▪ Ramkrishnan et al. (2007) ▪ Carneiro *et al*. (2012) ▪ Arroyo *et al*. (2013) ▪ Holloway and Parrish (2013) ▪ Arroyo and Gonzalez (2016) ▪ Weinheimer *et al*. (2017)	**An understanding of overall life cycle costs and savings** ▪ Conducting Lile cycle assessments ▪ Management of the whole life cycle of a building ▪ Considering operational savings over the lifecycle of a building ▪ Taking into account all processes along the lifecycle of the building and its components. ▪ Considering life cycle costs during material selections ▪ Possibility of reducing operational costs in advance
▪ Holloway and Parrish (2013) ▪ Valente *et al*. (2013) ▪ Wu and Wang (2016)	**Employee training and education** ▪ Training about LC principles, tools and techniques ▪ Training about SC principles, tools and techniques ▪ Integration of LC and SC training
▪ Vieira and Cachadinha (2011) ▪ Holloway and Parrish (2013)	**Corporate social responsibility** ▪ Positive impact on the environment ▪ Right things to do ▪ Moral and ethical obligations to preserve resources for future generations ▪ Moral role in contributing to the sustainable development of the planet
▪ Campos *et al*. (2012) ▪ Parrish (2013) ▪ Parrish and Whelton (2013) ▪ Maris and Parrish (2016) ▪ Weinheimer *et al*. (2017)	**The quest for Continuous improvement** ▪ Adopting Plan-Do-Check-Act (PDCA) cycle as a paradigm for continuous improvement ▪ Continuous learning to enhance social involvement and to inspire and motivate workers ▪ Continuous improvement as perpetual steps towards perfection and sustainable development ▪ Adopting Kaizen as a business philosophy to continuously improve all functions and processes and involve all employees
▪ Bae and Kim (2007) ▪ Holloway and Parrish (2013) ▪ Weinheimer *et al*. (2017)	**Commitment of owners to sustainability** ▪ Owner's attitude about sustainable building projects. ▪ The owner as the team member with the most influence on a project's sustainability ▪ Owner's opportunities to affect the sustainability outcomes of a project.
▪ Bae and Kim (2007) ▪ Ramkrishnan *et al*. (2007) ▪ Maund and London (2009) ▪ Novak (2012) ▪ Parrish (2012)	**Integrated design and project delivery methods** ▪ Integrated design ▪ Integrated supply-chain ▪ Project team coordination earlier in the project

▪ Sharma and Cui (2012) ▪ Holloway and Parrish (2013) ▪ Ghosh *et al*. (2014) ▪ Johnsen and Drevland (2016) ▪ Maris and Parrish (2016) ▪ Weinheimer *et al*. (2017)	▪ Stakeholder engagement ▪ Early contractor involvement ▪ Early involvement of specialty contractors and suppliers in design phase ▪ Contracts that support collaboration and information sharing such as the Integrated Form of Agreement (IFoA) ▪ Selection of right teams and people ▪ Projects not awarded based on lowest-price criteria ▪ Systems-thinking approach ▪ Integrated Project Delivery (IPD)
▪ Ahuja *et al*. (2014) ▪ Maris and Parrish (2016) ▪ Weinheimer *et al*. (2017)	**Building Information Modelling (BIM)** ▪ BIM as a friend of both lean and green philosophies ▪ BIM as a catalyst to develop synergies between lean and green. ▪ BIM as an effective process to achieve leanness and sustainability
▪ All studies within the SLR sample	**The focus on waste-minimisation of:** ▪ Material (Physical) waste ▪ Process (time) Waste ▪ TIMWOOD ▪ Non-value adding activities ▪ Waste of human potential ▪ Environmental Waste (e.g. pollution, carbon emissions, energy and water consumptions). ▪ Social Waste (e.g. accidents and injury rates, unhealthy and unsafe practices) ▪ Unnecessary costs (e.g. re-work and resource depletion) ▪ Designing-out waste
▪ Gomez *et al*. (2015) ▪ Weinheimer et al. (2017)	**The Lean Architectural Technologist (AT) as key player in the green value chain** ▪ Bridging the gap between conceptual design and production ▪ Multi-objective decision making in generating green value ▪ Addressing the gap between design and green technology management ▪ Lean AT as a technical designer skilled in construction technology ▪ Lean AT as the creative partner in the value chain
▪ Klotz and Horman (2007) ▪ Campos *et al*. (2012) ▪ Parrish (2012) ▪ Johnsen and Drevland (2016)	**Visual management and transparency of processes** ▪ Flow of information between workers and project managers ▪ Process mapping and visibility (i.e. Value stream mapping) ▪ Transparency in communications ▪ Trustful collaboration and information-sharing between project-team members ▪ Visual controls of production

Opportunities for future research on LC and Sustainability

A comprehensive list of gaps and opportunities for further work has been collated (Table 5). Interestingly, many of these research opportunities are still unfilled and could potentially help to overcome many, if not all, of the flaws and limitations in approaches to LC and SC identified by this study in Tables 2 and 3 above.

Table 5 Opportunities for future research on integrating LC and sustainability

Author(s) and Year	Categories and Subcategories
▪ Salvatierra-Garrido and Pasquire (2011) ▪ Vieira and Cachadinha (2011) ▪ Novak (2012) ▪ Holloway and Parrish (2013) ▪ Wu and Wang (2016) ▪ Saggin *et al*. (2017)	**Empirical Studies** ▪ Conducting empirical studies to capture the measurable benefits of integrating LC and sustainability ▪ Empirical studies quantifying and highlighting life-cycle costs and pay-back periods to further support growth in sustainable construction ▪ Empirical studies to investigate the relationship of the specific project-centric values with company sustainability-values, and the impact on project processes. ▪ Empirical studies to explore how Lean Design can contribute to enhancing client and social values from an early stage of projects.
▪ Luo et al. (2005) ▪ Bae and Kim (2007) ▪ Emuze and Smallwood (2013) ▪ Golzarpoor and Gonzalez (2013) ▪ Ahuja et al. (2014)	**New Frameworks** ▪ Developing a BIM-based framework for supporting and measuring LC and sustainability improvements ▪ Developing a multi criteria decision-making framework to support the selection of various lean construction practices for sustainable facilities ▪ Development of methodology that would allow the integration of H&S, lean and sustainability for the delivery of project value in construction
▪ Huovila and Koskela (1998) ▪ Salvatierra-Garrido and Pasquire (2011) ▪ Novak (2012) ▪ Golzarpoor and Gonzalez (2013) ▪ Arroyo and Gonzalez (2016) ▪ Weinheimer (2016)	**Wider Definitions** ▪ Developing a broader list of wastes to eliminate and to account for environmental and social wastes in all project´s lifecycle stages ▪ Examining the opportunity for project 'value' to be understood relative to a broader perspective of global sustainability value ○ Project value expressed as economic, social & environmental value ○ Widening the concept of value in LC to consider society and future generations as potential customers ▪ Identifying and eliminating sources of waste that occur within the process of obtaining a sustainable building certification
▪ Bae and Kim (2007) ▪ Parrish (2012)	**New Metrices** ▪ Developing an empirical relationship matrix between LC practices and green practices related to environmental

▪ Valente *et al*. (2013)	certifications (e.g. BREEAM) ▪ Developing and implementing new cost paradigms (e.g. value-led) when evaluating sustainability options ▪ Evaluating JIT and pre-fabrication techniques from a holistic perspective to increase the sustainability of a construction project.
▪ Bae and Kim (2007) ▪ Parrish (2012) ▪ Arroyo et al. (2012) and (2013 ▪ Valente et al. (2013) ▪ Weinheimer et al. (2017)	**New Techniques** ▪ Using lean Value Stream Mapping and Choosing by Advantages techniques for supporting sustainability choices and purposes ▪ Incorporating sustainability plans for purchase and installation of sustainable materials and equipment into LPS look-ahead plans
▪ Holloway and Parrish (2013) ▪ Gomez et al (2015)	**Roles and Responsibilities** ▪ Assessing the changing roles and responsibilities of project stakeholders in sustainable construction projects ▪ Investigating the Architectural Technologist's role in linking LC and sustainability

Conclusions and Recommendations

The aim of this study was to systematically review and critically assess the research progress made by the IGLC community, over a span of 25 years, in relation to integrating LC and sustainability principles. A systematic approach is still relatively rare in reviews, particularly in construction management literature. Promoting a systematic approach to scholarly reviews can help to advance the standard of academic rigor. SLRs are valuable for their ability to synthesise and uncover connections between separate studies, describe directions for future research, and provide implications for practice and policy. Thus, the main contribution in this paper is the conceptual consolidation of a growing body of knowledge from the IGLC community in a critical and systematic way, which has led to novel and important contributions to knowledge.

Firstly, the findings of this study revealed the slow up-take and limited amount of existing research on the topic (only started in 1998 with a total of 41 studies to date). These 41 studies were conducted in, or produced by authors from, 14 different countries, with USA and Brazil leading the research and practice of this topic (more than 50% of all publications). The study also revealed that only 10% of the reviewed studies were conducted to empirically implement and quantify the measurable benefits of integrating LC and sustainability. Accordingly, it is suggested that empirical studies in relation to LC-SC integration need to move from being simply focused on conceptual or practical investigations to the addition of deeper analysis and the quest for research evidence, which can help to influence policy and practice.

Secondly, the analysis and consolidation of findings of extant literature led to the development of a wider identification and conceptualisation of synergies and inconsistencies between LC and SC approaches (Figure 6). Thirdly, three major limitations

in approaches to LC emerged out of the analysis of this study: (1) The predominance of a 'limited' customer-focused perspective of 'Value'; (2) The limited focus on the management of project life-cycle requirements; and (3) The prevailing conceptualisation of 'Waste', which does not account for environmental and social impacts. However, two major limitations were associated with approaches to SC: (1) The over-reliance on formal 'Green Performance Certifications', which limits opportunities for sustainability improvement; and (2) Approaches to sustainability in architecture and construction that assume 'fixed input-output relations'. Fourthly, a list of key enablers for integrating principles of LC and SC at strategic, tactical and operational levels of a construction project has been developed (See Table 4). Finally, a thorough analysis of research reviewed in this study led to the identification of significant gaps in knowledge and opportunities for improvement that remain unfilled (Table 5). Tackling these identified flaws and exploiting the opportunities for future research collated by this study could certainly help to move the research agenda forward and potentially lead to sustainable improvements in practice.

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Appendix 1 – Coded studies

Year	Author(s)	Paper title	Research Methodology	Research purpose
1998	Huovila and Koskela	Contribution of the Principles of Lean Construction to Meet the Challenges of Sustainable Development	Literature Review	Conceptual Investigation
2002	Degani and Cardoso	Environmental Performance and Lean Construction Concepts - Can We Talk About a Clean Construction	Literature Review	Theoretical Integration
2005	Luo et al.	Lean Principles for Prefabrication in Green Design-Build Projects	Case Study Using DSR	Practical Investigation
2007	Ramkrishnan et al.	Green Building Rating and Delivery Systems in Building Construction_ Toward AEC+P+F Integration	Literature Review	Conceptual Investigation
2007	Klotz and Horman	Transparency, Process Mapping and Environmentally Sustainable Building	Case Study	Empirical Implementation
2007	Bae and Kim	Sustainable Value on Construction Project and Application of Lean Construction Methods	Case Study	Practical Investigation
2008	Bae and Kim	Assessing the Environmental Impacts of Lean Supply System_ A Case Study of High-Rise Condominium Construction in Seoul, Korea	Case Study	Practical Investigation
2009	Maund and London	Integrated Supply Chain Construction Ecosystem Management	Case Study	Practical Investigation
2009	Koskela and Tommelein	The Economic Theory of Production Conceals Opportunities for Sustainability Improvement	Case Study	Empirical Implementation
2011	Maia et al.	A Systemic Approach to the Concept of Value and Its Effects on Lean Construction	Case Study	Practical Investigation
2011	Vieira and Cachadinha	Lean Construction and Sustainability - Complementary Paradigms_ A Case Study	Literature Review	Theoretical Integration
2011	Salvatierra-Garrido and Pasquire	The First and Last Value Model_ Sustainability as a First Value Delivery of Lean Construction Practice	Literature Review	Theoretical Integration
2012	Campos et al.	Relation Between the Sustainable Maturity of Construction companies and the philosophy of lean construction	Case Study	Empirical Implementation
2012	Sharma and Cui	Subsidy Allocation Mechanism for Successful Implementation of Green Contracting Strategies	Literature Review	Theoretical Integration
2012	Rosenbaum et al.	Green-Lean Approach for Assessing Environmental and Production Waste in Construction	Practice-Oriented Examination	Practical Investigation
2012	Arroyo et al.	Deciding a Sustainable Alternative by Choosing by Advantages' in the AEC industry	Literature Review	Theoretical Integration
2012	Parrish	Lean and Green Construction_ Lessons Learned from Design and Construction of a Modular LEED Gold Building	Critical Review	Conceptual Investigation
2012	Novak	Value Paradigm_ Revealing Synergy Between Lean and Sustainability	Illustrative Case Studies	Practical Investigation
2012	Carneiro et al.	Lean and Green_ A Relationship Matrix	Case Study	Practical Investigation
2013	Parrish and Whelton	Lean Operations an Energy Management Perspective	Case Study	Practical Investigation

2013	Golzarpoor & Gonzalez	A Green-Lean Simulation Model for Assessing Environmental and Production Waste in Construction	Case Study	Practical Investigation
2013	Arroyo et al.	Using 'Choosing by Advantages' to Select Tile From a Global Sustainable Perspective	Critical Review	Conceptual Investigation
2013	Holloway and Parrish	The Contractors Self-Perceived Role in Sustainable Construction_ Survey Results	Literature Review	Theoritical Integration
2013	Valente et al.	Lean and green 2013_how both philosophies can interact on strategic, tactical and operational levels of a company	Literature Review	Conceptual Investigation
2013	Emuze and Smallwood	The Integration of Health and Safety (H&S), Lean and Sustainability in Construction_ A Literature Review	Case Study	Practical Investigation
2014	Ghosh et al.	A Case Study to Examine Environmental Benefits of Lean Construction	Literature Review	Theoritical Integration
2014	Salem et al.	Reducing Environmental, Economic, and Social Impacts of Work-Zones by Implementing Lean Construction Techniques	Case Study	Practical Investigation
2014	Abduh et al.	Green Construction Assessment Model for Improving Sustainable Practices of the Indonesian Government Construction Projects	Case Study	Practical Investigation
2014	Ahuja et al.	BIM Based Conceptual Framework for Lean and Green Integration	Literature Review	Conceptual Investigation
2015	Vasconcelos et al.	Guidelines for Practice and Evaluation of Sustainable Construction Sites: A Lean, Green and Wellbeing Integrated Approach	Pilot Study	Practical Investigation
2015	Belayutham and Gonzalez	A Lean Approach to Manage Production and Environmental Performance of Earthwork Operation	Surveys and Interviews	Practical Investigation
2015	Saggin et al.	Comparing Investments in Sustainability with Cost Reduction from Waste Due to Lean Construction	Survey	Practical Investigation
2015	Gomez et al.	Generating Value at Preconstruction_ Minding the Gap in Lean Architectural Practice	Literature Review	Theoritical Integration
2016	Fuenzalida et al.	Evaluating Environmental Impacts of Construction Operation Before and After the Implementation of Lean Tools	Semi-Structured Interviews	Practical Investigation
2016	Weinheimer	The Process of Green Building Certification_ An Examination Regarding Lean Principles	Case Study Interviews	Practical Investigation
2016	Arroyo and Gonzalez	Rethinking Waste Definition to Account for Environmental and Social Impacts	Critical Review	Theoritical Integration
2016	Maris and Parrish	The Confluence of Lean and Green Construction Practices in the Commercial Buildings Market	Literature Review	Conceptual Investigation
2016	Wu and Wang	A Critical Review of the Factors Affecting the Success of Using Lean to Achieve Green Benefits	Case Study Interviews	Practical Investigation
2016	Johnsen and Drevland	Lean and Sustainability_ Three Pillar Thinking in the Production Process	Literature Review	Conceptual Investigation
2017	Weinheimer et al.	Green Building and Lean Management_ Synergies and Conflicts	Literature Review	Conceptual Investigation & Theoretical Integration
2017	Cunha and Lima	Analysis of the Influence of Lean Construction and LEED Certification on the Quality of Construction Sites	Case Study	Empirical Implementation