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A literature review

Solaimani, Sam; Sedighi, Mo

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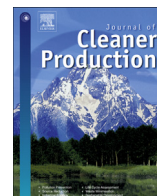
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Toward a holistic view on lean sustainable construction: A literature review

Sam Solaimani ^{a,*}, Mohamad Sedighi ^b

^a Center for Marketing & SCM, Nyenrode Business University, the Netherlands

^b Faculty of Architecture, Delft University of Technology, the Netherlands

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ABSTRACT

The need for sustainable built environment is pressing; an urgency that spans environmental, economic and social values of sustainability. Since late 1980s, the Lean philosophy has been adopted in the construction sector, with a focus on efficiency, predominantly as a function of economic competence. More recently, however, the Lean principles and practices have been revisited and increasingly used to create and preserve social and environmental values as well. The result was a growing, but dispersed, body of knowledge on sustainability and Lean construction, and hence, equivocal about how Lean contributes to sustainability. By means of a Systematic Literature Review (SLR) based on 118 journal articles from 1998 to 2017, this article aims to provide a comprehensive understanding of “how Lean helps achieve and maintain sustainability in construction sector”. The findings are structured into a holistic framework, which underlines a multidimensional approach toward sustainability, i.e., focus on stakeholders, across various construction phases, while simultaneously being heedful of concerns regarding people, planet, and profit. It became clear that the current body of knowledge is mainly skewed toward economic values, which calls for more research in the social and environmental aspects of construction. This study assembles a palette of existing best practices, based on which scholars’ and practitioners’ can balance their efforts across three dimensions of sustainability. Moreover, it identifies several under-researched areas of Lean sustainable construction that have the potential to be expanded in by future researchers.

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1. Introduction

The need for developing sustainable construction environments and methods is increasingly emphasized by ample of scholars and practitioners in this domain (e.g., Bae and Kim, 2008; Koranda et al., 2012; Lapinski et al., 2006; Nahmens and Ikuma, 2012; Rosenbaum et al., 2013) to serve people, planet and profit, the so-called ‘triple bottom line’ that focuses on social, environmental and economic concerns (Elkington, 2013). The sustainability dimensions are interdependent; as such, it can be argued that “the economy exists within society and the society exists within the environment” (Manley et al., 2008, p. 744). Hence, focusing on one dimension while compromising the other defeats the purpose. In fact, a synergetic interrelationship among the dimensions is advocated; one that busts the silos and ensures that all three dimensions are and remain working in concert (Elkington, 2013; Manley et al., 2008).

Creating and maintaining a synergetic triangle is, however, easier said than done (Campbell, 1996). Consider the conflicts (i) between environmental and social concerns for instance in the case of prefabricated construction that may be a strategy to potentially reduce the material waste, but may also create a rigid structure that limits customization and individual expression (Dao et al., 2011; Höök and Stehn, 2005), (ii) between economic and environmental interests such as use of solar panels and green roofs that may enable an energy neutral built environment, but lead to a higher capital cost (Dimond and Webb, 2017), and (iii) between economic and social concerns such as marginalized employees’ safety as a consequence of extremely cost efficient production site (Nahmens and Ikuma, 2009), to name a few.

In tuning in to an integrative approach to sustainability Lean philosophy is considered to be promising (Dües et al., 2013; Florida, 1996; Galeazzo et al., 2014; Pil and Rothenberg, 2003). In the late 1980s, Lean was popularized by an international best-selling book by Womack et al. (1990) based on their longitudinal study in Toyota Production System (TPS) operations. Shah and Ward (2007, p. 791) define Lean as “an integrated socio-technical system whose main

* Corresponding author.

E-mail address: s.solaimani@nyenrode.nl (S. Solaimani).

objective is to eliminate waste by concurrently reducing or minimizing supplier, customer, and internal variability". Lean found its way into the construction sector by Koskela (1992), which has led to series of studies, mainly revolving around value creation and efficiency improvement with focus on cost and waste reduction (e.g., Alsehaime and Koskela, 2008; De Treville and Antonakis, 2006). Along with a broader diffusion and more frequent application of Lean ideas, the link between Lean construction and social and environmental dimensions of sustainability became more prominent (Jørgensen et al., 2007; Nahmens and Ikuma, 2012; Ogunbiyi and Goulding, 2014).

About the same period, with an ever-growing network of involved stakeholders in construction, the emerging challenge of 'process orientation', or silo-busting integration of end-to-end actors began to attract the attention of more scholars (Elkington, 2013; Newman and Dale, 2005). In fact, equal and instant attention to all dimensions of sustainability is considered as a product of stakeholders' interactions and collective decision-making (Adolphe and Rousval, 2007; Deakin et al., 2002; Haapio, 2012; Yang et al., 2015).

While the interplay between involved actors is critical in establishing a sustainable modus operandi, the role and involvement of actors change throughout various phases of a project's lifecycle (Olander, 2007). A broadly accepted project lifecycle outlines four stages of conceptualization, planning, execution and termination (Adams and Barnd, 1983; King and Cleland, 1983). The former two phases focus on explication of projects' primary goals, clients' needs and constraints, and a formalized planning to sketch the initial concepts, while the latter two phases, by and large, give an account of materials and resources needed in the project, building process, *ex post* adjustments and maintenance (e.g., Guggemos and Horvath, 2003; Guo et al., 2010; Kerzner, 2001; Pinto, 1988). To avoid overcomplication, this paper adheres to a simplified version of the discussed phases, i.e., Extraction & Processing and Logistics & Distribution for suppliers, Design & Planning and Build & Delivery for developers, and Co-creation & Occupancy for customers (c.f., Ibbs et al., 2003; Dixit et al., 2012). Evaluation and assessment of sustainability and performance indicators span across these six phases (Fregonara, 2017).

As argued earlier, the literature on Lean and sustainable construction is substantial, but largely focused on isolated topics, typically with narrow technical scope, and consequently, over the past decades it has become considerably scattered. This study sets out to explore how Lean has contributed to an end-to-end construction field in relation to sustainability. Hence, the foci of analysis spans across various stages of construction, various stakeholders involved, and from economic, environmental and social perspectives. There are a few literature studies in the areas of Lean construction; however, these studies are either limited to a specific area of construction (i.e., Mandujano et al., 2016 [based on 28 publications] with a focus on waste in virtual design), focus on Lean and sustainability without a specific attention to construction (i.e., León and Calvo-Amodio, 2017 [based on 57 publications]; Martínez-Jurado and Moyano-Fuentes, 2014 [based on 58 publications]), remain descriptive in nature, and therefore, lack an explanation of the relationship between Lean and the triple bottom line (i.e., Carvalho et al., 2017 [based on 48 publications]), while generally based on relatively small samples sizes. More importantly, the involvement and role of actors, across multiple stages of construction has not been part of earlier studies.

The remainder of this paper is structured as starting with a detailed account of the research method, including the review process and criteria, leading to a summary of the research findings. By structuring the analysis of extracted literature along three dimensions of sustainability, stakeholders and construction phases, a

gestalt view of Lean sustainable construction is established. Finally, the paper concludes with a discussion on how the findings can be interpreted from an academic and practical viewpoint.

2. Research method

To aggregate evidence on Lean construction and sustainability, a comprehensive SLR is carried out. SLR facilitates "theory development, closes areas where a plethora of research exists, and uncovers areas where research is needed" (Webster and Watson, 2002, p. 13). SLR is not a descriptive summary of articles; it calls for a synthesis of publications to develop an integral understanding of a theory (Okoli and Schabram, 2010). Fink (2019) defines SLR as "a systematic, explicit, and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners." (p. 3). As such, this approach enables a transparent and replicable way to identify, evaluate, and synthesize the existing literature (Fink, 2019), while minimizing biases and errors (Tranfield et al., 2003).

To ensure rigor throughout of the process, this study adhered to the three broadly accepted steps of planning the review, conducting the review, and reporting and dissemination (Green and Higgins, 2008; Tranfield et al., 2003). Accordingly, the purpose and boundaries of the study were determined first, i.e., focusing on articles that explain 'how Lean contributes to sustainable construction'. The search terms included Lean, construction and sustainability (see Fig. 1). Note that some search terms include "*" which enables the search to be broader, for instance, "sustain*" includes "sustaining", "sustainable" and "sustainability". In preserving data reliability, the search was limited to peer-reviewed journal articles. The search was not restricted to a certain period, and only articles published in English were included. The relevant articles were found in one of the most prominent search engines, namely Scopus. To make sure that no relevant articles were overlooked, the repositories of several relevant journals in the fields of construction, sustainability and operations management; for instance, Automation in Construction, International Journal of Construction Management, Journal of Cleaner Production, Sustainable Cities and Society, Journal of Sustainability, were directly searched. By looking into both streams, i.e., search engine and publishers' repositories, the output was compared, and search consistency is checked, while 13 not indexed articles were identified (i.e., snowball searching).

The collected articles were first cleaned up where duplicates and inaccessible articles were removed. Next, the relevance of the selected articles was carefully assessed. In this step, the articles' title, abstract and keywords were screened and excluded if irrelevant. For example, some papers were referring to Lean as an adjective (e.g., 'lean fuel'), verb (e.g., 'leaning on'), noun (e.g., 'lean rollcrete'), or applying 'social network analysis' in project planning context. The included articles were subjected to a full-length screening. In this step, the articles were fully scrutinized and relevant frameworks, figures, statements, propositions, and findings were highlighted and annotated. Overall, the relevance was based on whether or not the articles explicitly address the impact of Lean on sustainable construction. As such, the exclusion was applied to articles that may underline economic, environmental and social aspects of sustainability, and yet without an explicit link to Lean principle and practices. To structure the process, from selection to analysis, a Microsoft Excel-based database was developed where all the descriptive data, including research method, sample size, geographical details, industry, theoretical foundation, scope, execution type and projects typology, as well as analytical insights including the link between Lean and sustainable construction, were systematically registered. The database is available upon request.

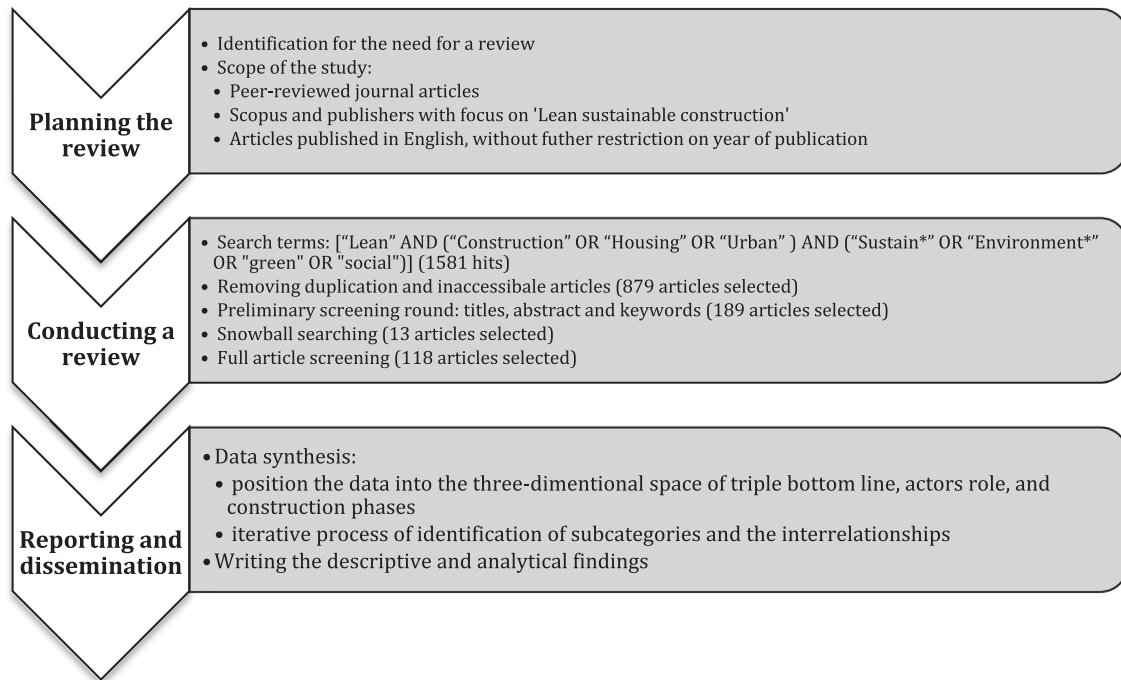


Fig. 1. The SLR process.

Initially, the data is positioned along a three-dimensional space conform to triple bottom line, actors' role and construction phases. Some articles included multiple aspects, for instance, referring to both economic and environmental contributions of Lean from multiple stakeholders. Throughout the review process, relevant (often interrelated) subcategories in each dimension were identified. For instance, the environmental aspects as part of sustainability dimension were clustered into more detailed subcategories (e.g., value and waste, impact, design process). Also, the interrelationships were identified and registered (e.g., type of value and waste leading to environmental impact to be addressed by various design-oriented practices). Important to note is that clustering was an iterative process where categories, subcategories and their interrelationship were subject to change each time new insight was identified. The findings emulated a tree structure where a vast range of Lean principles and practices, first, classified into three types of stakeholders, then across different phases.

Although SLR follows a strict, structured and transparent process, the decisions around selection and analysis of articles are subjective in nature. To alleviate authors' bias, the involvement of more than one reviewer is advocated (Tranfield et al., 2003). On this account, the authors collaboratively conducted the data collection and analysis through parallel screening of sources, iteratively reviewing the articles independently, juxtaposing the individual output, and discussing the differences and discrepancies until a consensus was reached on how to label, cluster, interrelated and report.

3. Findings

With respect to descriptive insights, it is worth noting that although the concept of Lean construction was introduced in 1992, the first articles that started to emphasize the link between Lean and sustainability in construction appear in 1998. From this point, the attention of academic community started to grow incrementally (Fig. 2a), but globally with USA, UK and India on the top,

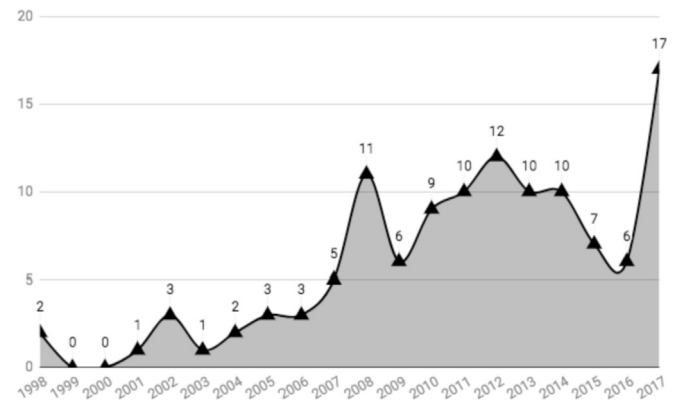


Fig. 2a. Trend of publication between 1998 and 2017.

implying the construction sectors interest for Lean construction, as well as its general applicability to be applied across countries and continents (Fig. 2b). Note 30 articles are not empirical but based on conceptual reasoning, literature review (i.e., Ansah and Sorooshian, 2017; Bajjou et al., 2017a,b), simulation, scenario analysis, hence are not on this chart. Methodologically speaking, case study—out of which 40 single case and 18 multi-case studies—appears to be the most frequently applied research method. The next most popular appear to be multi-method, conceptual and simulation, which suggest that quantitative research, as well as experiments, design research and ethnographical studies are relatively scarce (Fig. 3a). The top 10 publishers seem to be mainly from the domain of construction engineering and construction management, which hints at scant attention of other relevant publishers including those

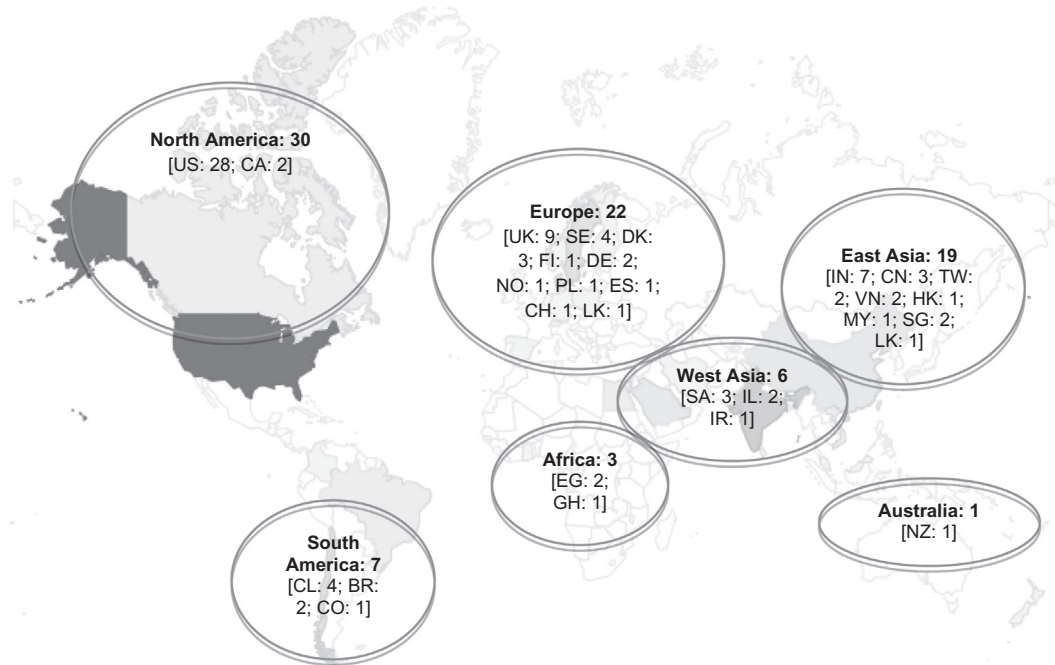


Fig. 2b. The spread of empirical studies across the world.

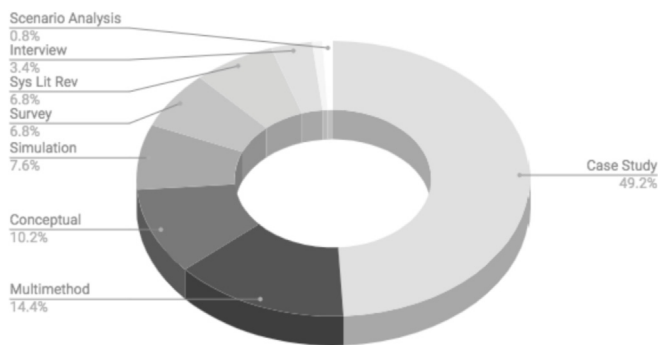


Fig. 3a. Applied research methods.

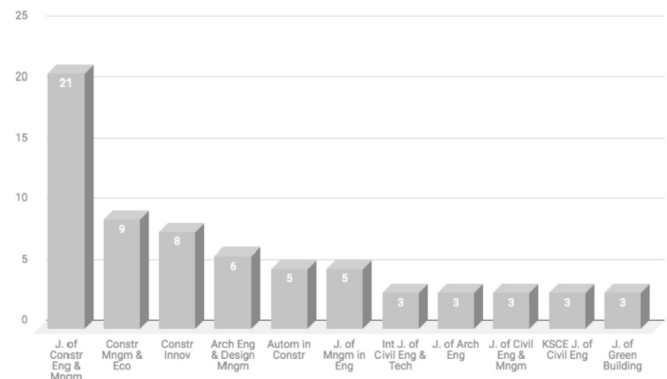


Fig. 3b. Top 10 publishers.

focused on sustainability in general (Fig. 3b).

Among seven types¹ of construction projects, most studies appear to be generic in nature; with the exception of housing projects, the other construction types have not received proportional attention, leaving out context-specific peculiarities and needs (Fig. 4a). As presented in Fig. 4b, the most frequently recurring topics in the areas of Lean and sustainability appear to be process flow, Just-in-Time (JIT) and waste reduction. Note that waste reduction is equivocal, as the economic and environmental impact are inherently interdependent (i.e., any type of economic waste reduction has an environmental impact and vice versa), and therefore, it can be positioned as both economic and environmental. Moreover, it appears that the economic dimension has received comparatively the most attention, and the environmental dimensions seem to be least refined.

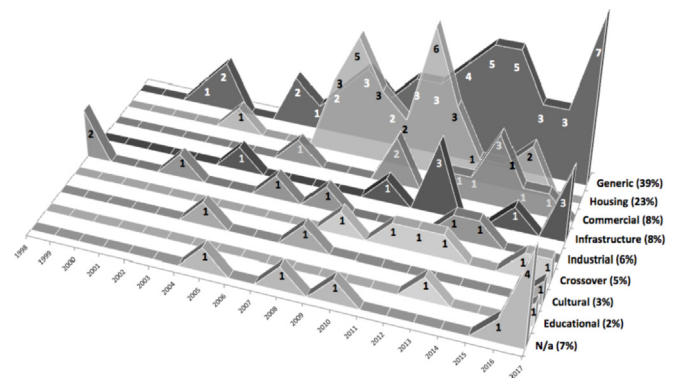


Fig. 4a. The spread of construction typology across years.

¹ The applied construction typology includes crossover (e.g., hospital, polyclinic, pharmacy), commercial (e.g., shopping mall, office), housing (i.e., residential building), cultural (e.g., museum, culture centre, movie theatre), administrative (e.g., ministries, headquarter), recreational (e.g., attraction park), industrial (e.g., manufactory), ru(e.g., parking-garage, service buildings), educational (e.g., schools, university) construction entities.

To generate analytical insights, as discussed in the outset of this paper, the literature is structured across the triple bottom line, considering the role of typical stakeholders involved across various

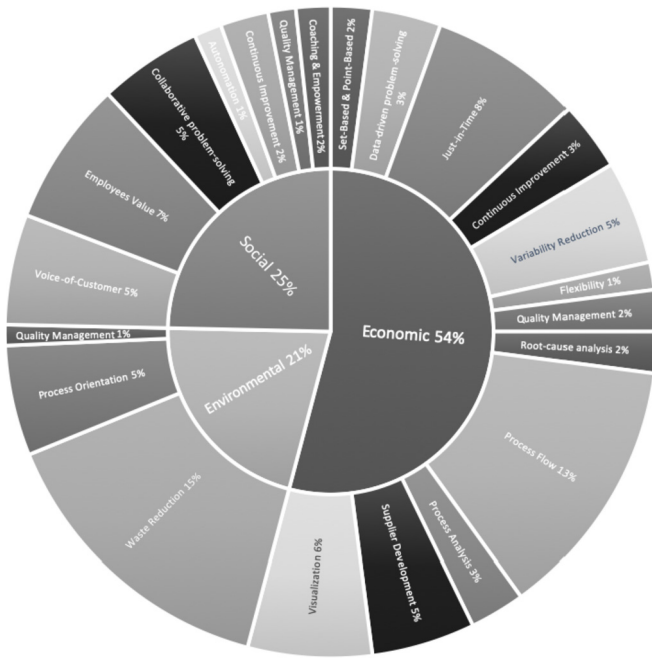


Fig. 4b. Lean principles and practices for sustainable construction.

phases of construction. To keep the complexity manageable, key actors are divided into supplier (responsible for extraction & processing and logistics & distribution), developer (responsible for design & planning and build & delivery), and customer (involved in design or co-creation and occupancy). Accordingly, the remainder of this writing details how the literature describes and prescribes the potentials of Lean for sustainable construction.

3.1. Economic view

Economic values are expressed in terms of efficient use of resources and effective transformation process, based on a systemic understanding of value, customers' needs and consumption process (Nahmens, 2009; Nahmens and Ikuma, 2012).

3.1.1. Supplier

In the construction context, suppliers are companies that typically are responsible for raw material extraction, processing, transportation to warehouses as well as construction fields and distribution centers, packaging and storing, and delivering built resources, mostly in the shape of physical supplies such as goods and materials (Kelley, 2013). As construction is becoming more complex, suppliers are becoming specialists, and supply chains are increasingly transforming from linear hierarchical entities into dynamic network of interacting entities (c.f., designing building dictionary).²

3.1.1.1. Extraction & processing. In mass production settings, pull-based production strategy (i.e., producing only when there is an actual demand) can effectively (i) lower the inventory costs (Ko, 2010), especially when combined with judicious buffers, e.g., consolidated centers (Sacks and Partouche, 2010), and (ii) minimize variability in product choice (Nahmens and Mullens, 2009). JIT appears to be another application of pull-based production which

ensures that the right quantities of material are delivered to the right location in right condition at the right time (Koranda et al., 2012; Low Sui and Choong Joo, 2001). Typical wastes which JIT can address are waiting for material delivery at the production site, unnecessary transportation as a consequence of incomplete material deliver, and excessive material delivery on construction sites (Khanh and Kim, 2014; Sandberg and Bildsten, 2011; Sarhan et al., 2017).

To implement a pull approach, as an alternative to tendering, a long-term relationship and commitment with suppliers seems to be the commended Lean approach (Green and May 2005; Naim and Barlow, 2003). Long-term commitment requires trust and confidence between partners, for which slow revisions and update, last-minute or inaccurate demands, and late deliveries are to be prevented (Low Sui and Choong Joo, 2001). However, in practice the last-minute updates and changes are not always avoidable, and hence, synchronization-based models are suggested for improving early on-site data sharing between stakeholders (Tsai et al., 2007).

Building real-time feedback loops in the stakeholders network facilitate and incentivize information sharing which is a priority within Lean approach (Tommelein, 1998). Information sharing and cooperative attitudes can be enhanced by shifting from contract-based relationships toward trust-based relationships (Ozorhon et al., 2013). According to Pestana et al. (2014) mediocre communication, between suppliers and developers (e.g., designers and subcontractors), particularly in the early design phase (e.g., the design submittal process) leads to poor transparency and performance, and rework at the end. From a Lean standpoint, supplier development in general, and 'early supplier involvement' in specific, helps reduce the design related issues given the fact that design complexity exacerbates in later stages (Ladhad and Parrish, 2013; Reifi and Emmitt, 2013).

3.1.1.2. Logistics & distribution. Waste identification and elimination are the hallmark of Lean thinking. An example of waste in suppliers setting is minimization of site transportation (earlier discussed from a JIT perspective). To achieve this, in line with the Lean concept of small batches, a reduction of the quantity of stacks—for instance through 'panelization' plan³ (Shewchuk and Guo, 2012)—is recommended. In addition, a pull-driven resource allocation (Ng et al., 2013) and project planning is suggested; preferably, on a project-by-project basis to address the projects' idiosyncrasies and specific needs (Tommelein, 1998). Still, a collaborative effort seems to be more long-lasting. In fact, collaborative decision-making with and among suppliers is suggested to be continued in logistical processes (Green and May 2005), for instance, for trouble-shooting purposes at the construction sites (Nahmens and Mullens, 2011). To this end, cross-functional teamwork (Ghosh and Robson, 2015; Pasquire, 2012; Whelton et al., 2002) and suppliers peer review (i.e., subcontractors monitoring themselves in addition to the general contractor evaluations) (Sage et al., 2012) are some preferred Lean approaches.

For a seamless flow of material in large production sites, such as prefab manufacturing plants, Mullens (2008) stresses the importance of continuous improvement (or 'Kaizen' in Lean terminology), for instance, by means of the so-called Rapid Productivity Improvement (RPI) events. In RPI, a multidisciplinary team walks through the plant and makes various charts; examples include spaghetti charts, which visualizes movements and congestions to identify problematic areas and to make suggestions on how the

² Available at: https://www.designingbuildings.co.uk/wiki/Suppliers_for_design_and_construction.

³ Panelization plan specifies how to divide the interior walls of a building into prefabricated panels by determining what panels go into each stack and how they should be arranged and the stack drop-off location.

layout—and thus the flow of men, material, machines— can be improved. Equally interesting is the Value Stream Mapping (VSM) approach, which is a systematic, end-to-end, visualization tool that often is used to identify non-value-adding activities and to feed root-cause analysis (Barathwaj et al., 2017; Freire and Alarcón, 2002; Praveenkumar et al., 2015; Reijula et al., 2016; Rosenbaum et al., 2013; Yu et al., 2009, 2013). Similarly, 5S (Sort, Set in order, Shine, Standardize, and Sustain) is a recommended approach to organize the workspace by identifying and removing sources of waste, and ensuring process flow and efficiency (Sandberg and Bildsten, 2011; Shewchuk and Guo, 2012).

3.1.2. Developer

In building projects, suppliers are commissioned by developers who mainly are involved in design and planning (i.e., policy making and design-decision, construct plans, and blueprinting and computation), building (also re-develop and refurbishing) and delivery. While smaller developers generally sell developments once they are completed (trader developers), larger developers may retain developments, building up large portfolios of property, in effect acting as a property investor (investor developers). Developers include roles such as (sub)contractors, consulting engineers and designers, and policy makers in broader perspective (McQuade, 2008).

3.1.2.1. Design & planning. From the developer perspective, the literature seems to attach importance to visualization, as an effective way to bring design shortcomings to light and prevent financial loss early in the process, for instance, through process design pattern analysis (Breit et al., 2008). Note that design and planning is not a linear process, and in fact, involves iterations, sometimes with unnecessary repetition and rework as result (Kpamma and Adjei-Kumi, 2011). To overcome repetition and rework in design process, several Lean practices, such as design structure matrix, set-based and point-based design are suggested (Lee et al., 2012). Similar to the context of supplier, also for developers, establishing collaborative teams seem to be effective in identifying and rapid response to design issues and orchestrating cross-team planning (Ghosh and Robson, 2015; Sacks and Partouche, 2010). In terms of layout, co-location of design experts appears to accelerate the decision-making process (Aquere et al., 2013), while ceaseless attention for performance (quantitative) indices—e.g., bottleneck, rework, batches size, cycle time— feed the process with relevant insights (Tribelsky and Sacks, 2011).

When it comes to planning, the Last Planner System (LPS) is often stressed. Inspired by Lean thinking, LPS prioritize what “can” be done instead what “should” be done (Ballard, 2000). LPS, together with Work-In-Progress (WIP) buffering strategies or safety stock (Court et al., 2009), help improve planning reliability and to tackle variability in complex and dynamic production environments (Aziz and Hafez, 2013; González et al., 2009; González et al., 2008; Issa, 2013).

To reap the full potential of LPS, it is suggested to use the planning approach combined with visualization tools and process modeling and analysis tools, particularly with a high extent of granularity (e.g., real-time and near real-time data) (Alsehaimi et al., 2014; Chamberlin et al., 2017; Sacks et al., 2010b). Such data can also be used for planning (fluctuation) controls, such as FIFO-lane-based systems, which decouples consecutive tasks so that each task only deals with variation caused by the preceding task (Yu et al., 2009). To ensure data reliability in LPS, the use of spreadsheets in combination with error-proof functions (or ‘Poka Yoke’ in Lean terms) is suggested (Zaeri et al., 2017). From an organizational viewpoint, establishing foremen, training participants, client representation in planning, and dedicated

communication channels are considered critical conditions in using LPS (Vignesh, 2017).

The value that Lean attaches to visualization and systematic measurement is manifested by the literature’s emphasis on various virtual simulation tools – sometimes referred to as Virtual Design and Construction (VDC), that are used in design and planning phases (Mandujano et al., 2016) and carried forward in construction and facilities management. Examples of software packages discussed in the literature are ARENA, CAD, Extend + BPR, Revit, TEKLA (Abbasian-Hosseini et al., 2014; Al-Sudairi, 2007; Björnfort and Jongeling, 2007; Farrar et al., 2004; Lee and Cho, 2012). In the same vein, various modeling approaches are promoted, including Discrete Event Planning model (Golzarpoor et al., 2017), and Monte Carlo simulation (Erol et al., 2017). The simulation tools are often part of a larger systems; the so-called Building Information Modeling (BIM) (Ahuja et al., 2017). BIM is a combination of various tools and systems that enable digitalization and management of information flow and construction objects and processes (Sacks et al., 2010a).

Simulation techniques are suggested to be combined with other tools and systems such as animation tools like 3D Max (Han et al., 2012), production scheduling systems or ‘Heijunka’ (a Lean term for ‘production leveling’) (Bryde and Schulmeister, 2012), quality controls (Liu and Shi, 2017), project value stream management (Wen, 2014), and procurement planning (Yin et al., 2014). Additionally, BIM is often used to facilitate teamwork (Zhang et al., 2017), and reduce coordination-related problems, for instance, among main contractor’s site team and subcontractors, vendors and other units (Mahalingam et al., 2015).

3.1.2.2. Build & delivery. Much the same as for suppliers, developers also benefit from a streamlined process flow with minimized delays and disruptions (Andújar-Montoya et al., 2015). According to Sacks (2016), flow in construction can be understood along three dimensions of portfolio, process and operations, which refers to “flow of projects in regional construction economy, flow of locations within a project, and flow of trade crew in and between the location of projects” (p. 654). The main obstacle in achieving flow is variability, which can be identified with 5-whys, A3 reports, fishbone (or ‘ishikawa’) diagrams (Anderson and Kovach, 2014; Paez et al., 2005; Tommelein, 2015; Tsao et al., 2004; Zimina et al., 2012) and reduced with adaptable workforce management capabilities (Thomas et al., 2002), preventing quality issues and optimum sequencing of activities (Mitropoulos and Nichita, 2010) and standardization. Both supplier and developers can achieve a higher level of efficiency by preventing the unnecessary effort to reinvent the figurative ‘wheel’. The true potential of standardization can be unleashed when applied to repetitive processes. Some best practices are uniform building components (as opposed to unique components), uniform procedure for maintenance of equipment (Höök and Stehn, 2008; Sacks and Partouche, 2010; Yu et al., 2009).

Some other ways to improve flow are reducing batch size or ‘one piece flow’, for instance, single apartment finishing works instead of full floor (Nowotarski and Pasławski, 2016), multitasking and eliminating handovers (Sacks et al., 2007; Sacks and Goldin, 2007; Yu et al., 2009), mitigating bottleneck (Chua and Shen, 2005), and identifying and eliminating waste and non-value adding activities, such as unnecessary movements, excessive inventory, and unproductive meetings (Garrett and Lee, 2010; Khanh and Kim, 2014; Nahmens and Ikuma, 2012; Sandberg and Bildsten, 2011). That being said, for tools to be effective, contextual adjustments seem needed (Salem et al., 2006). Also, workers’ engagement and motivation is key (Höök and Stehn, 2008).

Quality is one of the recurring principles present in the

literature (quality will also be discussed from an environmental viewpoint). To enhance quality and prevent costly inefficiencies in production processes, data can be collected (e.g., observations, video recording, images, RFID and GPS sensors) and analyzed (Cabrerá et al., 2012). Better yet, anomalies in production can proactively be detected and immediately resolved (i.e., 'Jidoka' in Lean terminology); however, detection does not need to be automated per se as employees can be empowered to inspect processes for defects and errors themselves (Nikakhtar et al., 2015).

3.1.3. Customer

Customer (or client) is the cornerstone of any construction project that basically defines what should and should not be considered as value. In effect, customer is rarely a single person, even in relatively small projects. Customer can be the owner of the project's output, the end-user, or actors with close ties to the end-user including promoter, purchaser, and principal (McQuade, 2008).

3.1.3.1. Co-creation. The distinction between value and non-value is not always straightforward (Mao and Zhang, 2008). From a Lean perspective, waste and non-value adding processes and output can largely be prevented through participatory design and co-creation with customers (Gülyaz et al., 2019). For instance, before completing the blueprint (Sandberg and Bildsten, 2011), delaying a product configuration decision can be used to secure more time to collect more details of customers' requirements (Naim and Barlow, 2003). Further, visualization of customers' needs and wishes, particularly in the early phases of design, for instance, with visualization tools such as four-dimensional computer-aided design (4D CAD), Computer Advanced Visualization Tools (CAVT), Virtual Prototyping (VP), and Design for Logistics (DFL), helps process transparency, and hence easier identification of costly waste (Li et al., 2008; McQuade, 2008; Rischmoller et al., 2006; Sacks et al., 2009). Also, pilot studies, especially in 'real-life' setting are promoted in Lean construction literature (Dave et al., 2016; Sacks and Goldin, 2007).

3.1.3.2. Occupancy. Among others, the role of customers is manifested by the 'takt' rate (Sacks and Partouche (2010)). Takt rate is the pace of production calculated in such way that the customer order is fulfilled without any delay. Clearly, takt rate follows the earlier discussed pull-production; a system that is triggered by customer (Lu et al., 2011), and hence, the role of a 'system integrator', one that focuses on end-to-end servicing and information sharing across the supply chain is indispensable (Crowley, 1998). Therefore, communication and transparency should transcend the dyadic relationship between supplier and developer, and prevail across the entire supply chain, including customers (Tommelein, 1998). Mass-customization and personalization fit within the same close-knit relationship with customers (Andújar-Montoya et al., 2015).

3.2. Environmental view

The environmental values involve a harmonic combination of assorted values including waste and pollution reduction, optimized energy consumption and natural resource use, and green manufacturing and logistics (Nahmens and Ikuma, 2012; Pasquire and Salvatierra-Garrido, 2011).

3.2.1. Supplier

3.2.1.1. Extraction & processing. In the extraction and processing phase, distinction between environmental value and waste is the starting point. In addition to process analysis tools like VSM, adopting LEED⁴ principles, awareness about material recyclability, green gas effects, water sources and reclaimed water use are a few topics that can feed mapping and assessment of value and waste (Lapinski et al., 2006; Praveenkumar et al., 2015). Retrospectively, environmental impact analysis, especially with the involvement of sustainable building experts, helps an in-depth understanding of the projects' ecological footprint (Castro-Lacouture et al., 2008).

3.2.1.2. Logistics & distribution. From a logistical viewpoint, the concept of quality management and waste reduction are emphasized. At this phase, flawed material estimation and ordering seem to be the source of excessive transportation, and hence, excessive carbon emissions (Banawi and Bilec, 2014). Transportation and material handling is where materials are often damaged, leading to unnecessary write-offs and excessive wastage (Nahmens and Ikuma, 2012).

3.2.2. Developer

3.2.2.1. Design & planning. In the design phase, adaptability toward developing partners can be created by working with modular design components which divide a project into independent manageable sub-units or 'work chunks' (Ghosh and Robson, 2015; Hansen and Olsson, 2011). The result seems to enable a more environmentally conscious design and planning; e.g., contractors are stimulated to consider concrete recycling earlier in the design stage (Song and Liang, 2011).

3.2.2.2. Build & delivery. In the post design and planning phase, the identification of key drivers of resource waste appears to be critical (Nahmens and Ikuma, 2012; Senaratne and Ekanayake, 2012; Wu et al., 2013). Relevant examples in the context of developers are redesigning the on-site fabrication yard with low inventory and smooth workflow to achieve low-carbon installation (Wu et al., 2013) and energy consumption monitoring and regulation to achieve net-zero classification (Ladhad and Parrish, 2013). Similar to economic considerations, the earlier discussed JIT approach seems to be promising in diminishing environmental waste (such as vehicle discharges), yet not often applied by construction firms (Dixit et al., 2017). One way to achieve JIT is by relying on regional material to reduce delivery time and minimize stocking, while releasing less CO₂ (Koranda et al., 2012).

In terms of environmental impact, an important nuance is that larger construction projects seem to benefit more from the Lean concepts in comparison with small-scale rural projects. The main reason is structure and efficiency inherent to large scale operations marked by more schedule control, as well as financial resources (Koranda et al., 2012). Notwithstanding, Lean transformation appears to be relatively 'easier' in small projects given the less complicated operations and more flexible organizational culture toward change (Gülyaz et al., 2015).

3.2.3. Customer

3.2.3.1. Co-creation. Understanding and interaction with the customer remains critical. In this respect, Thyssen et al. (2010) developed a series of workshops to gain a better understanding of customers' needs. As part of the workshop, the focus is not only on utility and function, but also environmental aspects including lifespan, durability and renewability of parts.

3.2.3.2. Occupancy. Throughout and after execution and delivery phase, the role of an environmentally conscious customer is critical.

⁴ Leadership in Energy and Environmental Design (LEED) is a guide as the standard for sustainable building.

This awareness can be achieved through training and education about recyclable or reusable material and environment-friendly practices and operations (Song and Liang, 2011). However, perhaps more important is the establishment of a cohesive working culture where employees are stimulated to remain environmentally conscious in their daily operations, and being encouraged to performance with less ecological waste (Galeazzo et al., 2014; Govindan et al., 2014; Mollenkopf et al., 2010; Yahya and Mohamad, 2011).

3.3. Social view

Compared to economic and environmental concerns, the social aspects are hardest to quantify (Dillard et al., 2009). In the context of Lean construction, the social values involve protection of human well-being throughout projects life-cycle, varying from human and community development, fair labor practices, human health, and equal opportunity (Bae and Kim, 2008; Nahmens and Ikuma, 2012).

3.3.1. Supplier

3.3.1.1. Extraction & processing. In addressing the social side of sustainability, engagement with supply partners seems most effective as a way to stimulate and establish formal best practices for local communities, for instance, with restrictive policies regarding relocation of township, employment opportunities, infrastructure, equality, wellness and healthcare (Bryde and Schulmeister, 2012; Pavez et al., 2010; Reifi and Emmitt, 2013).

3.3.1.2. Logistics & distribution. Improved working conditions, including improved safety with advanced driver-assistance systems, policies around driver fatigue, ergonomic driver's seat, are key (Jørgensen and Emmitt, 2008); however, policies and tools are effective when employees comply with the quality standards and procedures and proactively seek for improvements (Vinodh et al., 2011). In this respect, high intrinsic motivation and 'sense of ownership' are needed for acceptance and participation (Gao and Low, 2014), which can be stimulated with more coaching and empowerment (or autonomy) (Forrester, 1997).

3.3.2. Developer

3.3.2.1. Design & planning. A close proximity of designers seems to have a positive impact on communication and knowledge exchange, team spirit, and working environments (Aquere et al., 2013). Also, the diversity of design teams with involvement of professionals from various disciplines and backgrounds stimulates a learning environment (Ko and Chung, 2014). In terms of planning, although safety is mainly considered in the building and delivery phase (to be discussed next), coupling health, safety and LPS is recommended (Forman, 2013).

3.3.2.2. Build & delivery. From a social viewpoint, the concept of 'autonomation' appears to be of particular interest in the production phase (Saurin et al., 2008). It refers to the employees' autonomy to stop production in case of abnormality in preventing safety hazards, including awkward postures, chances of accidental contact with cutting tools, fatigue from less walking to get materials and tools, chance of pinch point for foot/leg, and reduced chance of muscle strain from kicking blocks in place (Ikuma et al., 2011; Nahmens and Ikuma, 2012). Another social aspect is the earlier discussed concept of modularity, which appears to help minimize movements, and hence reducing manual handling and inherent risks of injury. One solution to this comes through 'modularization', where components are often moved and lifted with machines and not manually (Court et al., 2009; James et al., 2014; Yin et al., 2014). Similarly, process automation helps detect and reduce risks

involved in manual handling (Rozenfeld et al., 2010).

Visual management is another practice that seems to be effective in stimulating employees' engagement (Kasiramkumar and Indhu, 2016). Tezel and Aziz (2017b) posit that visualization has a positive impact on self-management, team coordination, Plan Percent Complete (PPC), control, and workplace conditions. Moreover, a more leveled workload, and hence, fair labor intensity and performance expectation can be ensured with tools like performance charts (Bryde and Schulmeister, 2012). In addition, preserving balance between workload and the assigned labor capacity (Mitropoulos and Nichita, 2010), optimal working hours (Senaratne and Ekanayake, 2012), and mentorship for continuous improvement appear to be promising (Reifi and Emmitt, 2013; Sandberg and Bildsten, 2011).

3.3.3. Customer

3.3.3.1. Co-creation. The social aspect of customer centricity is a vital element of Lean construction (Andújar-Montoya et al., 2015; Pasquire and Salvatierra-Garrido, 2011; Reijula et al., 2016). Lean literature promotes the concept of 'voice-of-customer', which denotes an in-depth understanding of customers' contextual needs, desires and constraints (Jørgensen and Emmitt, 2008, 2009; Pasquire and Salvatierra-Garrido, 2011; Wandahl, 2015; Yahya and Mohamad, 2011). For instance, in sketching customers' requirements, aside from functional and utilitarian aspects, attention should be given to customers' individual visions and dreams, habitual behavior, and cultural meaning of aesthetics (Thyssen et al., 2010). In the same way, the customers' macro necessities including socialization, security, access to educational facilities, and accessibility are to be respected (Pasquire and Salvatierra-Garrido, 2011).

3.3.3.2. Occupancy. Customer centricity continues at the stage of occupancy, mainly with a focus on safety. In this regard, earlier discussed tools like Poka Yoke' and visual management are put forth. Some examples of this are automatic electrical circuit lockout as a preventive measure, and use of safety signs, visual demarcations and boards to stimulate safety through visuals (Bajjou et al., 2017a,b; Gambatese et al., 2016; Pavez et al., 2010; Tezel and Aziz, 2017a). Table 1, which in short is called the Glean Construction framework (a blend of Green and Lean) by the authors, provides a concise overview of the discussed Lean principles and practices across various phases and stakeholders in relation to the triple bottom line of sustainability.

4. Discussion and conclusion

In synthesizing the literature into a holistic structure, it appears that the Lean principles and practices are useful in largely all the facets of construction process, across various phases and stakeholders. Without any mathematical pretense, a modeling tool from system dynamics known as a causal-loop diagram is used to illustrate the relationships and interdependencies discussed so far (Fig. 5). System dynamics is a modeling approach proposed by Forrester in early 60s (Forrester, 1997) that helps gain insight into dynamic complex systems. Given the complexity inherent to sustainability in supply chain and environmental management, more and more studies in this area use system dynamics tools and techniques (Dong et al., 2012; Georgiadis and Besiou, 2008; Yuan and Wang, 2014).

In figure seven, it is apparent that out that almost all the Lean principles and techniques seem to have a positive impact (or a 'reinforcing' effect) on triple bottom line across the construction process. Focus on quality management leads to more standardization, which implies variability reduction, leading to a lower

Table 1

Lean principles and practices across construction phases and stakeholders: the GLean construction framework.

Lean construction principles and practices with impact on sustainability			
Economic	Supplier	Extraction & Processing	Pull-based production (Ko, 2010)
			Consolidated warehousing (Sacks and Partouche, 2010)
			Minimizing variability (Nahmens and Mullens, 2009)
		Logistics & Distribution	JIT production (or extraction) (Koranda et al., 2012; Low Sui and Choong Joo, 2001; Khanh and Kim, 2014; Sandberg and Bildsten, 2011; Sarhan et al., 2017)
			Long-term relationship and commitment (Low Sui and Choong Joo, 2001; Naim and Barlow, 2003; Stuart Green and May 2005)
			Continuous communication and information sharing (Pestana et al., 2014; Tommelein, 1998; Tsai et al., 2007)
	Developer	Design & Planning	Early Supplier Involvement (Ladhad and Parrish, 2013; Reifi and Emmitt, 2013)
			Waste reduction (e.g., excessive transportation) (Shewchuk and Guo, 2012)
			Small batches (e.g., penalization) (Ng et al., 2013)
		Build & Delivering	Collaborative decision-making (Stuart Green and May 2005; Nahmens and Mullens, 2011)
			Cross-functional teamwork (e.g., suppliers peer review) (Ghosh and Robson, 2015; Pasquire, 2012; Sage et al., 2012; Whelton et al., 2002)
			End-to-end analysis (e.g., VSM) (Barathwaj et al., 2017; Freire & Alarcón, 2002; Praveenkumar et al., 2015; Reijula et al., 2016; Rosenbaum et al., 2013; Yu et al., 2009, 2013)
Environmental	Supplier	Extraction & Processing	Continuous improvement (Kaizen for PRI events, visualization) (Mullens, 2008)
			5S (Sandberg and Bildsten, 2011; Shewchuk and Guo, 2012)
			Visualization (Breit et al., 2008)
		Logistics & Distribution	Design structure matrix, set-based and point-based design (Lee et al., 2012)
			Cross-team planning (Aquere et al., 2013; Ghosh and Robson, 2015; Sacks and Partouche, 2010; Tribelsky and Sacks, 2011)
			LPS (Aziz and Hafez, 2013; Court et al., 2009; González et al., 2009; González et al., 2008; Issa, 2013)
	Developer	Design & Planning	LPS in combination with visualization (Abdullah Alsehaimi et al., 2014; Chamberlin et al., 2017; Sacks, Radosavljevic, et al., 2010)
			Poka Yoke (Zaeri et al., 2017)
			Virtual design (Abbasian-Hosseini et al., 2014; Al-Sudairi, 2007; Björnfort and Jongeling, 2007; Erol et al., 2017; Golzarpoor et al., 2017; Farrar et al., 2004; Lee and Cho, 2012)
		Build & Delivering	BIM in combination with simulation techniques (Ahuja et al., 2017; Han et al., 2012; Liu and Shi, 2017; Yin et al., 2014; Wen, 2014)
			BIM in combination with Heijunka (Bryde and Schulmeister, 2012)
			BIM for teamwork (Mahalingam et al., 2015; Zhang et al., 2017)
Social	Supplier	Extraction & Processing	Process flow (Andújar-Montoya et al., 2015; Mitropoulos and Nichita, 2010; Salem et al., 2006; Thomas et al., 2002)
			Process flow and variability (5-whys, A3 report, Ishikawa) (Anderson and Kovach, 2014; Paez et al., 2005; Tommelein, 2015; Tsao et al., 2004; Zimina et al., 2012)
			Process flow and reducing batch size (one-piece flow) (Nowotarski and Paslawski, 2016)
		Logistics & Distribution	Process flow and multitasking and eliminating handovers (Sacks et al., 2007; Sacks and Goldin, 2007; Yu et al., 2009)
			Process flow and bottleneck (Chua and Shen, 2005)
			Process flow and waste elimination (Garrett and Lee, 2010; Khanh and Kim, 2014; Isabelina Nahmens and Ikuma, 2012; Sandberg and Bildsten, 2011)
	Developer	Design & Planning	Process flow with responsible and motivated workers (Höök and Stehn, 2008)
			Standardization (Höök and Stehn, 2008; Sacks and Partouche, 2010; Yu et al., 2009)
			Jidoka (Cabrera et al., 2012; Nikakhtar et al., 2015)
		Build & Delivering	Participatory design (Naim and Barlow, 2003; Sandberg and Bildsten, 2011)
			Visualization (e.g., CAD, 4D, VP, DFL, CAVT) and waste elimination (Li et al., 2008; McQuade, 2008; Rischmoller et al., 2006; Sacks et al., 2009)
			Pilot studies (e.g., 'real-life' setting) (Dave et al., 2016; Sacks and Goldin, 2007)
Social	Supplier	Extraction & Processing	Takt rate (Lu et al., 2011; Sacks and Partouche, 2010)
			System integrator and communication toward customer (Crowley, 1998)
			Mass-customization and personalization (Andújar-Montoya et al., 2015; Gülyaz et al., 2015)
		Logistics & Distribution	LEED principles (Lapinski et al., 2006; Praveenkumar et al., 2015)
			Environmental waste and value (e.g., material recyclability, green gas effects, water sources and reclaimed water) (Castro-Lacouture et al., 2008)
			Minimizing waste (e.g., excessive transportation, excessive carbon emissions) (Isabelina Nahmens and Ikuma, 2012)
	Developer	Design & Planning	Careful material estimation and ordering (Banawi and Bilec, 2014)
			Modular design components (Ghosh and Robson, 2015; Hansen and Olsson, 2011)
			Recycling materials (Song and Liang, 2011)
		Build & Delivering	Low inventory and smooth workflow (Wu et al., 2013)
			Energy consumption monitoring (e.g., net-zero energy; CO ₂ emission) (Koranda et al., 2012; Ladhad and Parrish, 2013)
			JIT production (Dixit et al., 2017; Koranda et al., 2012)
Social	Supplier	Extraction & Processing	Co-creation workshops with focus on environmental aspects (e.g., lifespan, durability, renewability) (Thyssen et al., 2010)
			Educating environmental considerations (Song and Liang, 2011)
			Cohesive working environment with focus on environmental aspects (Galeazzo et al., 2014; Govindan et al., 2014; Mollenkopf et al., 2010; Yahya and Mohamad, 2011)
		Logistics & Distribution	Engagement with supply partners to establish formal and informal stimuli in favor of employees and community (Bryde and Schulmeister, 2012; Pavez et al., 2010; Reifi and Emmitt, 2013)
			Improved working conditions (Jørgensen and Emmitt, 2008)
			Receptive employees toward continuous improvement (Vinodh et al., 2011)
	Developer	Design & Planning	Intrinsic motivation and autonomy (Gao and Low, 2014; Forrester, 1997; Treville et al., 2005)
			Co-located team (Aquere et al., 2013)
			Collaborative learning and experimentation (Ko and Chung, 2014)
		Build & Delivering	Linking health and safety to planning (Forman, 2013)
			Safety with autonotation (Saurin et al., 2008)
			Employees' autonomy to stop production for the sake of safety hazards (Ikuma et al., 2011; Isabelina Nahmens and Ikuma, 2012)

(continued on next page)

Table 1 (continued)

Lean construction principles and practices with impact on sustainability	
Customer	2012)
	Safety with process automation (Rozenfeld et al., 2010)
	Reducing manual handling with modularity (Court et al., 2009; James et al., 2014; Yin et al., 2014)
	Visual management (Kasiramkumar and Indhu, 2016)
	Visualization and self-management (Tezel and Aziz, 2017b)
	Visual management with performance chart and weekly meetings (Bryde and Schulmeister, 2012)
	Balance between workload and labor (Mitropoulos and Nichita, 2010)
	Optimal working hours (Senaratne and Ekanayake, 2012)
	Equal opportunities for workers regarding continuous improvement (Reifi and Emmitt, 2013; Sandberg and Bildsten, 2011)
	Long-term commitment (Gao and Low, 2014)
Co-creation	Voice-of-Customer (Andújar-Montoya et al., 2015; Pasquire and Salvatierra-Garrido, 2011; Reijula et al., 2016)
Occupancy	Involvement in decision-making and understanding contextual needs (Jørgensen and Emmitt, 2008, 2009; Pasquire and Salvatierra-Garrido, 2011; Thyssen et al., 2010; Wandahl, 2015; Yahya and Mohamad, 2011)
	Fostering customers' macro necessities (Pasquire and Salvatierra-Garrido, 2011)
	Safety with Poka Yoke and visual management (Bajjou et al., 2017a,b; Gambatese et al., 2016; Pavez et al., 2010; Tezel and Aziz, 2017a)

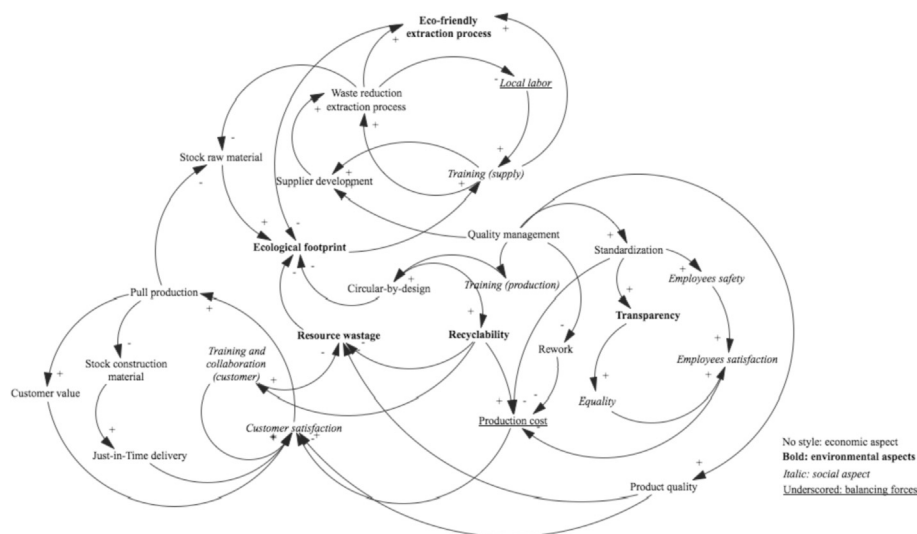


Fig. 5. Casual-loop diagram of Lean management in sustainable construction.

production cost (economic impact), a higher employees' safety (social impact), and more transparency (among others, materiality of environmental information). Similarly, error-proofing as part of quality management leads to less rework (economic impact), less resource spoilage (environmental impact), and less risky activities with possible harmful results (social impact), while recyclability or focus on circular economy, positively impact resource-efficient production (economic impact) with less negative ecological externalities including carbon dioxide emission, nitrogen discharge, and fluorosurfactants (or PFAS) pollution (environment impact).

However, there also appear to be several tradeoffs or 'balancing' forces. An optimized and efficient extraction site (economic measure) may lead to less job opportunities for a local community (social impact); design and production of circular products (environmental measure) may require more skillful workers (socio-economic impact); change in production method to ensure workers' safety (social measure) may lead to a higher production costs (economic impact); and standardization (economic measure) may lead to narrowly defined and intensified work (social impact).

All in all, it stands to reason that a multidimensional approach toward sustainability is imperative in construction. Accordingly, the main contribution of this study, to both scholars and practitioners, is the proposed holistic understanding of sustainability, where all three aspects of sustainability (i.e., the triple bottom line) are

equally valued, and attention is not limited to a part of supply chain. Instead, it takes a collaborative effort by supply chain partners, necessarily across the construction phases, to reach a shared vision on sustainable construction. After all, a company is only as sustainable as its suppliers (Krause et al., 2009). In this study, it is elaborated how Lean philosophy potentially can help optimize supply chain overall sustainability performance in different phases of construction, and enhance participation of stakeholders. The latter is a matter of importance as it highlights the reciprocal influence of multiple stakeholders on one another in shaping a sustainable built environment. That is not to say that possible conflicting forces within triple bottom line can be ignored. In fact, scholars and practitioners need to be cognizant of these potential tradeoffs, such as economic cost of quality, employees' safety and circular production vis-à-vis the socio-environmental tangible and intangible benefits.

Viewed from triple bottom line standpoint, the literature seems to largely overlook several promising Lean practices in context of construction including: innovation management, application of cutting-edge technologies, human resource management, locally-inspired practices, and end-to-end stakeholder collaboration. Increasingly, Lean scholars emphasize the potentials of Lean practices to boost firms' innovation capabilities (Solaimani et al., 2019a, b), which is a timely countermeasure to the construction industry's

conservatism (Havenvid et al., 2019). From a technological perspective, the applicability of Industry 4.0 trends such as Virtual/Augmented Reality to improved communication, particularly with customers, and Additive Manufacturing for advanced personalization possibilities (Sacks et al., 2009; Lim et al., 2012). From a social viewpoint, the importance of Lean Human Resource Management is underlined as an application that leads to a more empowered, engaged, and satisfied employees (Green, 2000). Environmentally speaking, the so-called locally-inspired practices, in particular employing locally available construction materials, techniques and human resources can be seen as a promising way to reduce ecological waste (Bredenoord et al., 2014). Beyond the common dyadic customer-developer and developer-supplier relationships, a more end-to-end networked collaboration leads to a broader mutual understanding about constraints and possibilities at all ends (Eriksson, 2010).

Although the present study may fall short in collecting all the existing papers on sustainability in construction –potential omissions could result from the underpinning literature being limited to Lean and peer-reviewed journal articles– it is the first attempt in calling attention for a multi-phase, multi-actor, with a multi-dimensional view on sustainability. From the same holistic view, future research can empirically substantiate our findings, likely by means of explorative research strategy including comparative case studies, longitudinal design research, and action research. During this study, it became clear that the economic side of Lean construction has received the most attention so far. Future studies are encouraged to take proportional notice of environmental and social aspects of Lean construction. Also, further research on potential conflicts and tradeoffs between economic, environmental and social dimensions of sustainability can contribute to the current understanding of holistic approach.

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Sam Solaimani is Associate Professor at Nyenrode Business University. Sam holds a PhD from Delft University of Technology, with focus on Business Model innovation in complex networked enterprises. He has obtained a MSc. (Cum Laude) on Business Information Systems from University of Amsterdam, and a BSc. on Information Science from Utrecht University. Sam's research focuses on Lean management, innovation management, digital transformation, and business model innovation. He has published in several peer-reviewed academic journals, some of which have recently appeared in the *Journal of Business Research*, *European Management Review*, *Electronic Markets*,

Information Systems Frontiers, *Technological Forecasting and Social Change*, and *Information Systems Management*.

Mohamad Sedighi graduated as an architect from TU Delft, and his PhD research focuses on re-thinking the architecture of appropriate habitats. Since 2010, he has been working as lecturer at IUST, and TU Delft. In 2013, he received an honorable mention certificate from Iran's Ministry of Urban Development for the design of a prototypical housing scheme, in Tehran; and in 2017, he was awarded a MIT grant by GAHTC. At present, Sedighi works as lecturer at TU Delft and as project developer at Dura Vermeer. Recently, he published 'Kuy-e Narmak (1952–1958): the growth and change of an urban community in Tehran' in the *Journal of Planning Perspectives*, and 'Shushtar-Nou (1975–85): A Forgotten Episode of Architectural Regionalism, Iran' in *International Journal of Islamic Architecture* (forthcoming).