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To cite this article: Xianhai Meng (2019) Lean management in the context of construction supply chains, International Journal of Production Research, 57:11, 3784-3798, DOI: [10.1080/00207543.2019.1566659](https://doi.org/10.1080/00207543.2019.1566659)

To link to this article: <https://doi.org/10.1080/00207543.2019.1566659>



Published online: 16 Jan 2019.



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## Lean management in the context of construction supply chains

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*(Received 22 December 2017; accepted 19 December 2018)*

Construction started its lean journey with learning from manufacturing. Unlike lean manufacturing, few studies to date have investigated lean construction in both breadth and depth, especially from the perspective of construction supply chains. The limited understanding of lean construction results in a research problem. This research aims to explore the implementation of lean principles in the context of project-based construction supply chains. It achieves its aim through an empirical investigation in the UK. A combination of quantitative and qualitative methodologies provides this research with validity and reliability. Lean principles are found applicable to both residential building projects and many other types of construction projects. It is also found that lean construction can be enhanced if it synergizes with supply chain collaboration. Another finding is that lean management has a significant impact on project performance. Nowadays, construction pursues best lean practices through both learning from manufacturing and developing its own paths. Similar to manufacturing, more and more construction projects adopt industrialised and standardised production and lean management with supply chain collaboration to become leaner. On the other hand, construction-specific management approaches and information technology (IT) tools are increasingly used in lean construction practices to maximise value and minimise waste.

**Keywords:** Lean management; supply chain collaboration; construction project; performance improvement; building information modelling

### 1. Introduction

Modern production systems have evolved from Taylor's mass production, through Ford's conveyor belt, to Toyota's lean production (Cil and Turkan 2013). Lean manufacturing has its origin from the Toyota production system in the Japanese automobile industry (Hines, Holweg, and Rich 2004). According to the Lean Enterprise Institute (LEI), the core idea of lean is to maximise customer value while minimising waste (LEI 2018). There are two main reasons for the emergence of lean manufacturing: one is the more advanced production methods and the other is the more demanding customers (Jasti and Kodali 2015). Since its launch in manufacturing, lean has been widely recognised as a powerful management system to improve the overall performance of an organisation (Bortolotti, Boscari, and Danese 2015). Nowadays, lean thinking has been introduced into many other countries and many other industries. An organisation can develop competitive advantages through adopting lean thinking as an innovative strategy.

In manufacturing, existing studies provide clear evidence in both depth and breadth for lean practices and their performance. Some of them adopt in-depth case studies. For example, Lacerda, Xambre, and Alvelos (2016) applied Value Stream Mapping for lean production in a Portuguese original equipment manufacturing company for the automobile industry to reduce cycle time and workforce cost. In order to drive systematic performance improvement, Thomas et al. (2016) implemented lean Six Sigma to overcome production challenges in a UK aerospace manufacturing company. Other studies on lean manufacturing are based on broad empirical information. For example, Filho, Ganga, and Gunasekaran (2016) conducted a questionnaire survey in Brazilian small and medium enterprises to assess the impact of lean implementation on manufacturing performance. Bevilacqua, Ciarapica, and Sanctis (2017) analysed the relationship among lean implementation, operational responsiveness and growth performance in manufacturing companies through an Italy-wide questionnaire survey.

In addition to internal lean practices within individual manufacturing organisations, existing studies pay attention to lean practices in the context of manufacturing supply chains. For example, Wee and Wu (2009) conducted an in-depth case study in the supply chain of a Taiwanese automobile manufacturing company to show how Value Stream Mapping supports lean supply chain management (LSCM) to improve product cost and quality. Chavez et al. (2015) completed an Ireland-wide questionnaire survey to link internal lean practices and supply chain partnerships because they believed

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that lean manufacturing is related to both internal operations and external processes, whose integration enhances performance improvement. For the studies on lean manufacturing in breadth, such as Chavez et al. (2015) and Filho, Ganga, and Gunasekaran (2016), they usually cover different types of manufacturing companies: aerospace, automobile, cement, chemicals, computer, electronics, food, furniture, medical equipment, metals, paper, petroleum, pharmaceuticals, plastics, rubber, textiles, wood, etc. As a result, manufacturing studies provide a systematic understanding of lean practices and their performance.

The construction industry is an important contributor to the economy in many countries. In the UK, the construction industry represents 6.5% of the total economy and employs 2.1 million people (Rhodes 2015). Construction has learned a number of new concepts and approaches from manufacturing (Behera, Mohanty, and Prakash 2015). Subsequent to the successful implementation of lean manufacturing, for example, construction has gradually adopted lean thinking in its practices (Paez et al. 2005). Compared to process-based manufacturing, construction is a project-based industry (Gann and Salter 2000). Construction distinguishes itself from manufacturing in terms of on-site and complex production (Salem et al. 2006). Unlike standardised products and repetitive processes in manufacturing, construction products are often customised and meanwhile the workflow in construction processes is often characterised by variability (Höök and Stehn 2008; Jørgensen and Emmitt 2008). Obviously, the traditional features of construction processes and activities challenge the adoption of lean thinking in the construction industry.

The applicability of lean principles to construction has attracted numerous research efforts. Relevant studies include Diekmann et al. (2004), Green and May (2005), Salem et al. (2006), Al-Sudairi (2007), Höök and Stehn (2008), Bryde and Schulmeister (2012), etc. Some of them suggest that construction should become more like manufacturing in order to adapt itself to lean methodology. For example, construction production needs greater industrialisation and standardisation. Others argue that lean construction is not a simple and direct copy of lean manufacturing. Instead, construction is inspired by lean thinking and should find new ways of project management that best suit its own particular circumstances to maximise value and minimise waste. According to the Construction Industry Institute (CII)'s report written by Diekmann et al. (2004), lean construction can be defined as the continuous process of eliminating waste, meeting all customer requirements, focussing on the entire value stream and pursuing perfection during a project. Although different people may have different voices about how to implement lean thinking appropriately in construction, there is a consensus that lean principles have a great potential to improve the delivery of construction projects (Al-Sudairi 2007).

In contrast with lean manufacturing, existing studies mainly focus lean construction on internal lean practices. For example, Pasqualini and Zawislak (2005) applied Value Stream Mapping in a Brazilian construction company to improve the performance of construction production. Nahmens and Mullens (2009) analysed the effect of product choice on lean implementation in two industrialised housing plants of the USA. Emmitt, Pasquire, and Mertia (2012) addressed the issues for process improvement when applying lean thinking in a small UK construction firm. Few studies to date provide evidence for the integration of lean construction and supply chain management, namely LSCM in construction. As a result, there is a doubt about lean management in the context of construction supply chains. According to Fearn and Fowler (2006), the weakness within existing studies can be identified as lean construction in isolation.

In the construction industry, there are various types of building construction projects, such as residential, educational, commercial, medical, sport, government and military buildings and civil engineering projects, such as highways, subways, tunnels and bridges. Existing studies tend to focus lean construction on residential building projects, such as houses and apartments. For example, Beary and Abdelhamid (2005) used lean tools, such as Six Sigma, for two apartment building projects in the USA to improve the production planning process. Björnfot and Stehn (2007) demonstrated value delivery in a Swedish timber housing project through the adoption of lean strategies. Based on a high-rise apartment building project in Israel, Brodetskaia, Sacks, and Shapira (2011) proposed a lean model and evaluated its impact on production workflow. Compared to other types of building construction and civil engineering projects with higher complexity, the production of residential buildings is relatively easily industrialised and standardised. It explains why residential building projects are dominant within existing studies on lean construction.

Some other types of building construction and civil engineering projects can also be observed within existing studies on lean construction. For example, AlSehaimi, Tzortzopoulos, and Koskela (2009) applied the Last Planner system, an IT (information technology) system specific to lean construction, in two university projects of Saudi Arabia. Andersen, Belay, and Seim (2012) investigated the performance of lean practices during Phase 2 of a Norwegian hospital building and compared it with the performance of traditional practices during Phase 1. Dave, Boddy, and Koskela (2013) identified the challenges and opportunities to integrate lean and building information modelling (BIM) in a UK highway project. Compared to existing studies on residential buildings, the number of existing studies in these types of building construction and civil engineering projects is much less. That is why the wide application of lean thinking to different types of projects in the construction industry is questioned by such people as Gosling and Naim (2009).

From the methodology perspective, most research efforts for lean construction utilise case studies. Few studies to date are based on broad empirical information. Although case study methodology is good at examining the use of lean approaches and tools, such as Value Stream Mapping, Six Sigma and Last Planner, in individual case projects, it is difficult to have a panoramic view of lean management in the whole construction industry. This makes lean construction studies different from lean manufacturing studies that provide clear evidence in both depth and breadth. As mentioned earlier, lean manufacturing studies in breadth attract attention from different types of manufacturing organisations. In contrast, concentration on some particular types of projects, especially residential building projects, through case studies prevents existing studies from generalising the applicability of lean construction and demonstrating the effect of lean construction on project performance. For all these reasons, there is a need for a new empirical investigation of lean construction.

This research attempts to bridge the knowledge gaps by answering the research questions about how well lean construction develops in different types of projects, why lean construction should integrate with supply chain management and whether lean construction has a significant impact on project performance. It investigates lean construction in both breadth and depth. It adopts a questionnaire survey and a series of expert interviews as a combined methodology. The objectives of this research include: (1) defining key indicators of lean construction; (2) identifying the possibility of applying lean principles to different types of construction projects; (3) determining the linkage between lean construction and supply chain management and (4) analysing the impact of lean construction on project performance. This research achieves its aim and objectives through an empirical investigation in the UK construction industry. It provides construction researchers and practitioners with useful information and knowledge to implement lean thinking. Although lean construction is the focus of this research, it is hoped that the information and knowledge provided by this research will also be useful for lean practices in other industries.

## **2. Key elements of lean construction**

Based on a review of relevant literature, customer focus, continuous improvement, waste minimisation, and learning and innovation are identified in this research as four key elements of lean construction. They are discussed in detail one by one in this section, each of which characterises a key aspect of lean construction.

### **2.1. Customer focus**

Customer focus is generally seen in terms of an organisation's ability to meet customer needs and achieve a high level of customer satisfaction (Barlow and Ozaki 2010). It is a central pillar of lean thinking (Gao and Low 2014). According to Salem et al. (2006), customers play a fundamental role throughout a construction project. For example, customer requirements should be explicitly defined for products or services through bids or contracts. Customer focus can be interpreted as 'only do work on request' (Zimina, Ballard, and Pasquire 2012). The real meaning behind customer focus is value creation and delivery because customer focus brings the best value products or services to customers (Fewing 2013). In order to satisfy the project client that is the end customer or represents end customers, designers, contractors and suppliers must have a good understanding of the client's business needs (Eriksson 2010). With client satisfaction in mind, they have to concentrate on value-adding processes and activities.

### **2.2. Continuous improvement**

Continuous improvement is synonymous with the continuous pursuit of perfection (Paez et al. 2005). It represents an endless search for excellence throughout a construction project (Fewing 2013). Lean construction requires continuous improvement effort because continuous improvement is about continuous maximisation of value (Diekmann et al. 2004; Koskela 2004). Problems are inevitable in any projects, including construction projects. Continuous improvement addresses working problems in an incremental and ongoing way (Emmitt, Pasquire, and Mertia 2012). Without continuous improvement, it is easy for project participants to quickly drift into ineffective and inefficient ways of working (Meng 2012). Continuous improvement must emerge and evolve simultaneously with a focus on process, people and long-term thinking (Meiling, Backlund, and Johnsson 2012). Lean techniques, such as Value Stream Mapping, are useful to develop continuous improvement (Freire and Alarcón 2002; Pasqualini and Zawislak 2005).

### **2.3. Learning and innovation**

Learning is the acquisition and development of skills, knowledge and experience. It is a basis of lean management (Bertelsen 2004). It can be divided into learning from internal sources and learning from external sources (Lantelme and Formoso 2000;

Fewing 2013). Learning from internal sources means that an organisation learns lessons from its own experience or past history while learning from external sources refers to learning from partner organisations or best practice organisations. Effective learning is useful to find the root causes of a problem and good solutions to the problem (Lange 2016). Learning leads to new thinking and new management that characterise innovation (Vakola and Rezgüi 2000; Bertelsen 2004). Innovation sustains lean construction implementation (Alves et al. 2009). Both learning and innovation are necessary for more efficient and effective ways of working to enhance lean construction (Barlow 2000; Green and May 2005).

#### 2.4. Waste minimisation

Wasteful processes and activities consume resources but do not add value to the final deliverables (Alves, Milberg, and Walsh 2012). Waste minimisation is an underlying principle for both lean manufacturing and lean construction because it removes all non-value-adding processes and activities. Diekmann et al. (2004) presented seven types of waste (overproduction, waiting, transport waste, extra processing, inventory waste, wasted operator motion and defect) and compared them between manufacturing and construction. With regard to extra processing, for example, manufacturing waste indicates doing more work than what is required while construction waste refers to rework, re-handling or restorage caused by a defect in design, fabrication or construction. Lean construction can be viewed as a powerful antidote to waste (Gao and Low 2014). It not only cuts 'fat' but also gets 'fitter' by concentrating on value-adding processes and activities (Terry and Smith 2011).

### 3. Research methods

In this research, a comprehensive review of relevant literature provides an up-to-date understanding of existing studies on lean manufacturing, lean construction and lean management in other industries. The literature review helps to identify how construction learned lean thinking from manufacturing and why construction was relatively slow to widely embrace the lean concept. It also helps to identify the key elements of lean construction. Based on the literature review, an urgent need is identified for an empirical investigation of lean construction, its linkage with supply chain management and its impact on project performance. The empirical investigation in this research adopts a combination of a quantitative questionnaire survey and a series of qualitative interviews. The quantitative questionnaire survey is in breadth while the qualitative interviews are in depth. The latter supports and complements the former. The combined methodology provides validity and reliability for this empirical research.

The questionnaire survey does not attempt to investigate the use of any lean systems, models, techniques and tools in construction projects. Instead, it aims to explore the implementation of lean principles in the context of project-based construction supply chains. The questionnaire survey targets the UK construction industry and its projects. It is project specific, which means that each response represents a construction project completed in the UK. Based on the key elements of lean construction identified from the literature review, four indicators of lean construction are defined in the questionnaire, including an emphasis on customer value, encouragement of learning and innovation, effort for waste minimisation and commitment to continuous improvement. These indicators have different meanings or implications for lean construction. That is why they are adopted in the questionnaire to describe different aspects of lean construction.

A considerable number of publications are reviewed in this research to identify the key indicators of lean construction. The sources of such publications include journal papers, conference papers, reports and books. They were published in the past two decades. Journal papers mainly come from *Journal of Construction Engineering and Management*, *Journal of Management in Engineering*, *Engineering, Construction and Architectural Management*, *Construction Management and Economics* and *Construction Innovation*, which are often recognised as the top five international journals in construction management. Papers published in *Lean Construction Journal*, an international journal specific to lean construction, are also reviewed in this research. In addition to construction journals, another literature source is general management and business journals, such as *Supply Chain Management*, that publish papers on lean construction and LSCM in construction. On the other hand, *Annual Conference of the International Group for Lean Construction* is the main source of conference papers. Industrial reports and research reports are also useful in this research to identify the key indicators of lean construction, which are mainly retrieved from the Construction Industry Institute (CII) in the USA and the Construction Industry Research and Information Association (CIRIA) in the UK.

Since the questionnaire survey is project specific, each respondent was required to answer the questionnaire based on a project in which he/she participated recently. The questionnaire consists of four sections. The first section is designed to collect the information about a respondent's position and experience as well as the nature of his/her organisation. The second section refers to the type of a project selected by the respondent and the type of supply chain collaboration in this project. The four indicators defined above are used in the third section to rate the level of lean management according to a four-point scale: very positive (VP = 1), positive (P = 2); negative (N = 3) and very negative (VN = 4). Time, cost and quality are



generally recognised as three major objectives of a construction project (Gardner 2015; Walker 2015). The fourth section allows the respondent to provide information about project performance in terms of time, cost and quality (see Appendix 1).

Subsequent to the development of a preliminary questionnaire, its workability was checked by a group of researchers and practitioners. Based on their comments and suggestions, the questionnaire was refined and improved accordingly. The finalised questionnaire was sent to around 300 construction practitioners in different regions of the UK through emails. The potential respondents were selected from industrial expert databases as well as other available sources. All of them had higher education backgrounds in relevant disciplines. For this reason, they had enough knowledge of lean principles. They all had more than 5 years of work experience in project management and/or lean management. Most of them possessed the professional memberships of the Chartered Institute of Building (CIOB), Institution of Civil Engineers (ICE) and/or Royal Institution of Chartered Surveyors (RICS). Their organisations played the roles of project client, designer, main contractor, specialist contractor or supplier of labour, materials and equipment (LME) in the surveyed projects. These roles represent suppliers at different tiers of a construction supply chain.

The questionnaire survey was followed by the interviews with 10 industrial experts in the UK. Expert interviews represent another in-depth methodology, which do not necessarily focus on individual case projects. Compared to a questionnaire survey that targets a large population, expert interviews take full advantage of direct interaction between people (Gillham 2000). Similar to the questionnaire respondents, the interviewees were selected from industrial expert databases as well as existing industrial links. The interviewees came from different organisational backgrounds, such as project client, designer, main contractor, specialist contractor and LME supplier. In doing so, it was possible to investigate lean construction from different perspectives. All the interviewees were knowledgeable and experienced in project management and/or lean management because they had received relevant education from universities and worked in relevant professional fields for at least 10 years. They held important management positions in their organisations (see Section 5). They were interviewed face to face or through the telephone. The interviews were semi-structured. An interview guide was well prepared to direct the conversations. Prior to each interview, the interview guide was sent to the interviewee so that he/she could have a good preparation in advance. Open-ended questions were used during each interview. The interviewees were asked to provide further information about the applicability of lean thinking to construction and the characteristics of lean construction. In addition to perceptions, the interviewees were encouraged to give real examples of lean practices in construction projects. The interviews were recorded with the interviewees' approval and then transcribed for later analysis.

#### **4. Analysis of questionnaire responses**

As a result of the questionnaire survey in this research, 104 completed questionnaires were returned with the response rate of around 35.0%. Among the 104 surveyed projects, 30.8% are educational buildings; 18.3% are commercial buildings; 14.4% are residential buildings; 8.7% are hospital buildings and 18.3% are other types of buildings, such as government buildings, sport buildings, military buildings and industrial buildings. In addition to building construction projects, 9.6% of the surveyed projects are civil engineering projects, such as roads, highways and bridges. The diversity of the surveyed projects in this research provides a possibility to investigate lean construction in a systematic way.

##### **4.1. Applicability of lean principles to construction**

As mentioned earlier, each indicator represents a key aspect of lean construction. Among the four indicators of lean construction, emphasis on customer value receives 79.9% of positive responses (including the responses to both Very Positive and Positive); encouragement of learning and innovation receives 68.6% of positive responses; effort for waste minimisation receives 77.7% of positive responses and commitment to continuous improvement receives 77.7% of positive responses. The finding provides clear evidence for the wide application of lean principles to construction in every key aspect. Although construction was relatively slow to embrace the lean concept, lean principles become widely accepted in construction projects today without compromise in any key aspect. Lean thinking helps construction projects to replace traditional management philosophies with new management paradigms. The wide embrace of lean thinking reflects the fact that the construction industry is extricating itself from the out-of-date management tradition. This is part of revolutionary changes that currently happen in the construction industry.

By comparison, encouragement of learning and innovation receives 11.3% less positive responses than an emphasis on customer value and 9.1% less positive responses than the effort for waste minimisation and commitment to continuous improvement. The distribution of positive responses received by different types of the surveyed projects is shown in Table 1 for each indicator of lean construction. For any type of the surveyed projects, it is clearly found in Table 1 that the positive responses of encouragement of learning and innovation are not as many as the positive responses of emphasis on the customer, the effort for waste minimisation and commitment to continuous improvement. As a result, an

Table 1. Positive responses of lean construction in different types of projects.

Lean construction indicator	Residential building <i>n</i> = 15	Educational building <i>n</i> = 32	Hospital building <i>n</i> = 9	Commercial building <i>n</i> = 19	Civil engineering <i>n</i> = 10	Other building <i>n</i> = 19	Total <i>n</i> = 104
Emphasis on customer value	86.7%	84.4%	77.8%	73.7%	60.0%	84.2%	79.9%
Encouragement of learning and innovation	80.0%	74.2%	66.7%	66.7%	50.0%	63.2%	68.6%
Effort for waste minimisation	86.7%	80.6%	77.8%	68.4%	80.0%	73.7%	77.7%
Commitment to continuous improvement	85.8%	81.3%	77.8%	84.2%	70.0%	63.2%	77.7%

unbalanced development of lean construction is observed in this research. Although encouragement of learning and innovation is relatively weak, it does not affect the general trend of progressive lean construction. As a traditional industry, the construction used to be reluctant to learn and innovate (Turner 2003; Zawdie 2012). It is inspiring that learning and innovation are encouraged in 68.6% of the surveyed projects, which implies that the construction industry has started its journey to active engagement in learning and innovation.

For each indicator of lean construction, as seen in Table 1, more positive responses are received from residential building projects than from any other types of projects in the construction industry. For example, the percentage of positive responses for commitment to continuous improvement in the group of residential buildings is 85.8% while this percentage is 84.2% in commercial buildings; 81.3% in educational buildings; 77.8% in hospital buildings; 70.0% in civil engineering projects and 63.2% in other building projects. The finding confirms that residential buildings are more likely to implement lean construction. This is because as mentioned earlier the production of residential buildings is relatively easily industrialised and standardised. However, it does not imply that lean construction cannot be implemented in other types of projects, such as educational, medical, commercial building projects as well as civil engineering projects, although their processes are more complex and dynamic. In this research, lean management can be found in different types of projects. As a result, it becomes possible to overcome the previous misunderstanding that lean principles are mainly applicable to residential building projects. Compared to previous studies, this research provides stronger support for the applicability of lean principles to construction.

#### 4.2. Lean construction at three levels of supply chain collaboration

In construction projects, there are three types of supply chain relationships: (1) non-collaboration between project parties; (2) short-term collaboration in a single project and (3) long-term collaboration in a continuous series of projects over a certain number of years. They describe supply chain collaboration at three different maturity levels. In this research, the analysis of questionnaire responses reports 31.7% of the surveyed projects without collaboration, 28.8% of the surveyed projects with short-term collaboration and 39.4% of the surveyed projects with long-term collaboration. Lean construction without supply chain collaboration is the so-called lean construction in isolation. Lean management with supply chain collaboration, either short term or long term, is evident in 68.2% of the surveyed projects. The finding indicates that lean implementation is often integrated with supply chain management in construction today. On the other hand, lean construction in isolation only remains preferred in a small proportion of projects. On the whole, the construction industry is going beyond the isolated constraints.

One-way analysis of variance (ANOVA) shows significant differences in mean values for emphasis on customer value and commitment to continuous improvement, but no significant differences in mean values for the encouragement of learning and innovation and effort for waste minimisation among the three groups (see Table 2). Since the questions about key indicators of lean construction are rated according to a four-point scale from very positive (VP = 1) to very negative (VN = 4), the smaller a mean value, the leaner the management in a certain aspect. No matter whether there are significant differences in mean values among the three groups or not, Table 2 clearly demonstrates that lean management with short-term collaboration is better than lean management without collaboration in all the four aspects. On the other hand, lean management with long-term collaboration is better than lean management with short-term collaboration in all four aspects. For example, the mean values of commitment to continuous improvement are 2.27 for non-collaboration, 2.14 for short-term collaboration and 1.90 for long-term collaboration, among which any latter one is better than any former

Table 2. Lean construction at three levels of supply chain collaboration.

Lean construction indicator	Supply chain collaboration			Total mean <i>n</i> = 104	ANOVA	
	Non-collaboration <i>n</i> = 33	Short-term collaboration <i>n</i> = 30	Long-term collaboration <i>n</i> = 41		<i>F</i>	<i>p</i>
Emphasis on customer value	2.27	2.17	1.95	2.12	3.796	0.026*
Encouragement of learning and innovation	2.34	2.28	2.10	2.23	1.385	0.255
Effort for waste minimisation	2.19	2.07	2.05	2.10	0.498	0.609
Commitment to continuous improvement	2.27	2.14	1.90	2.09	3.471	0.035*

\*Significance at 0.05 level.

one. Compared to lean construction in isolation, lean construction with supply chain collaboration, especially with long-term supply chain collaboration, is more successful. The finding describes a step-wise improvement of lean construction following the development of supply chain collaboration. In order to improve lean construction, developing supply chain collaboration is particularly important.

Pavnaskar, Gershenson, and Jambekar (2003) in manufacturing and Vrijhoef and Koskela (2000) in construction pointed out that waste problems are often caused by the inefficient and unreliable flow of information, materials and other resources. Lean production relies on the smooth workflow, in which various resources are required. Not only within individual organisations, information, materials and other resources also flow across the boundaries of customers and suppliers as supply chain partners. For this reason, Chavez et al. (2015) highlighted the importance of linking intra- and inter-organisational contexts for lean manufacturing. Similarly, Fearn and Fowler (2006) gave warning of the potential danger of applying lean thinking discretely in the supply chain of a construction project. Based on the better implementation of lean construction with supply chain collaboration, this research provides evidence to demonstrate the need for integrating lean construction and supply chain management. If supply chain partners collaborate with each other, it becomes more possible to smooth the workflow throughout the whole construction supply chain. As a result, there are greater opportunities to minimise waste and maximise value.

#### 4.3. Impact of lean construction on project performance

The questionnaire survey in this research gathers the information about the duration of a surveyed project; the certainty of whether the project is completed within a schedule or not and the delayed time if it is not completed within schedule. When a surveyed project is completed within schedule, the delayed time equals zero. Based on the above information, the percentage time delay can be defined as the ratio of delayed time to project duration. Similarly, it is possible to define percentage cost overrun as the ratio of overspent cost to project budget. Percentage time delay, percentage cost overrun and quality defect are considered as three performance indicators in this research. Spearman correlation is used to test the correlation between each lean construction indicator and each performance indicator. The test results are presented in Table 3. It is found that lean construction indicators are all positively correlated with any performance indicators. The finding demonstrates that the adoption of lean management has a positive impact on the improvement of project performance in terms of time, cost and quality.

As seen in Table 3, emphasis on customer value and commitment to continuous improvement are significantly correlated with any performance indicators. Encouragement of learning and innovation is significantly correlated with both cost and quality performance, whereas significance is not statistically evident for its correlation with time performance. The effort for waste minimisation is only significantly correlated with cost performance but not significantly correlated with time and quality performance. On the whole, the analysis of questionnaire responses provides evidence for the significant impact of lean construction on project performance. Lean thinking proves to be an important strategy to improve project performance and ensure project success. By comparison, it is an emphasis on customer value and commitment to continuous improvement that have a significant impact on project performance in a systematic way.

When comparing time, cost and quality performance, it is cost performance that is significantly influenced by all four indicators of lean construction. For any indicator of lean construction, the *p*-value for its correlation with cost performance



Table 3. Correlation between lean construction and project performance.

Lean construction indicator	Time performance		Cost performance		Quality performance	
	Correlation coefficient	<i>p</i>	Correlation coefficient	<i>p</i>	Correlation coefficient	<i>p</i>
Emphasis on customer value	0.200	0.044*	0.218	0.035*	0.205	0.037*
Encouragement of learning and innovation	0.109	0.279	0.307	0.003**	0.229	0.021*
Effort for waste minimisation	0.071	0.483	0.228	0.028*	0.137	0.169
Commitment to continuous improvement	0.196	0.050*	0.227	0.029*	0.198	0.046*

\*Significance at 0.05 level.

\*\*Significance at 0.01 level.

Table 4. Profile of interviewees.

No.	Organisation	Position
1	Client	Director of estate department
2	Client	Head of estate development
3	Designer	Design manager
4	Designer	Design consultant
5	Main contractor	Supply chain manager
6	Main contractor	Construction manager
7	Main contractor	Lean manager
8	Specialist contractor	General manager
9	Specialist contractor	Technical manager
10	LME supplier	Managing director

is always smaller than the *p*-value for its correlation with time performance and the *p*-value for its correlation with quality performance (see Table 3). For example, commitment to continuous improvement is significantly correlated with (1) cost performance at the 0.029 level; (2) quality performance at the 0.046 level and (3) time performance at the 0.050 level, among which 0.029 is smaller than 0.046 and 0.050. In statistics, the smaller the *p*-value is the closer correlation two variables have. Compared to time and quality performance, cost performance is more closely correlated with any indicator of lean construction. For these reasons, the adoption of lean construction is more important if the cost has a higher priority over time and quality among the three major project objectives. In other words, lean construction plays a more important role in cost performance improvement than in time and quality performance improvement.

## 5. Analysis of interview results

In this research, a total of 10 industrial experts were interviewed to collect further information about lean construction practices. A profile of the interviewees is presented in Table 4.

Extending lean manufacturing practices beyond a company's scope to the whole supply chain resulted in the emergence of LSCM as a new concept during the 1990s (Liu et al. 2013). In construction, lean practices in isolation have been criticised because discrete application of lean principles in a supply chain causes difficulties with regard to project delivery (Fearne and Fowler 2006). The analysis of questionnaire responses in this research reveals that lean construction with supply chain collaboration, especially with long-term collaboration, is more successful than lean construction in isolation. All the interviewees in this research supported the finding from the questionnaire analysis. In addition to smoothing the workflow, the interviewees believed that supply chain collaboration brings harmonious working relationships to project participants or supply chain partners, which enhance the effectiveness of lean practices. This is explained by the interviewees as another reason why lean construction should adopt the LSCM approach.

Several examples were given by the interviewees in this research as successful examples of lean construction, including a large airport terminal building project in the UK. This project is often recognised as a remarkable attempt to pursue best lean practices with supply chain collaboration. In this project, the Last Planner system was used to improve the reliability of work planning and support design and construction. A group of lean specialists was employed by the client of this project to assist designers, contractors and suppliers to improve project management processes and activities. Project parties, such as client, designers, contractors and suppliers, collaborated closely with each other to deliver products and services following lean principles, which was characterised by trust, reciprocity, openness, transparency, risk sharing, effective problem solving, etc.

Lean management with supply chain collaboration significantly contributed to waste minimisation and value maximisation in this project. As a result, this project was completed on time, on a budget, and with high quality.

On-site and complex production distinguishes construction from manufacturing (Salem et al. 2006). The nature of traditional production systems made it slow for construction to widely embrace the lean concept and methodology. According to the interviewees in this research, modern production in terms of industrialisation and standardisation is increasingly adopted in construction projects. The increasing trend is characterised by modular construction method (MCM), which is synonymous with industrialised building system (IBS). MCM or IBS refers to a production system in which standardised building components, elements or units prefabricated off-site in a plant are assembled on site into a building. At the initial stage of its application, MCM or IBS was mainly used for residential buildings. This explains why some existing studies, such as Höök and Stehn (2008), Nahmens and Ikuma (2012) and Yu et al. (2013), focus on the applicability of lean principles to MCM or IBS in residential buildings. The interviewees expressed that nowadays the increasing use of MCM or IBS can also be found in many other types of projects, such as educational buildings and hospital buildings. As a result, construction becomes more manufacturing based. In this sense, lean construction can be considered as an extension of lean manufacturing and meanwhile, it becomes easier for construction to break down the barriers to lean thinking.

Traditionally, design and construction were separated in a project (Fellows et al. 2002). The separation of design and construction was a root cause of many problems, e.g. the lack of constructability for the design. Early contractor involvement (ECI) is recognised as an innovative mechanism to overcome the separation of design and construction because it incorporates construction knowledge and experience into design decision-making (Song, Mohamed, and AbouRizk 2009). According to the interviewees in this research, ECI suits construction-specific situations for lean practices. If a new path of lean construction with its own characteristics like ECI is created, lean construction can be described as a diversion from lean manufacturing. ECI has many benefits for both designers and contractors. On one hand, it brings better ideas to design solutions and helps designers to identify and correct any design errors as early as possible. On the other hand, it ensures the ease of construction and enables contractors to better plan construction processes and activities in advance. The use of ECI offers more opportunities to maximise value and minimise waste. It also promotes supply chain collaboration, especially collaboration between designers and contractors, which in turn enhances lean practices.

So far, there have been three industrial revolutions in manufacturing: (1) Industry 1.0 from the eighteenth century to the end of the nineteenth century; (2) Industry 2.0 from the end of the nineteenth century to the 1980s and (3) Industry 3.0 from the 1980s to the 2010s (Yin, Stecke, and Li 2018). Currently, Industry 4.0 is a new initiative for the fourth industrial revolution, which is mainly characterised by IT and digital innovations. Buer, Strandhagen, and Chan (2018) identified the linkage between Industry 4.0 and lean manufacturing because they support each other. The interactive relationship between Industry 4.0 and lean manufacturing is confirmed by other manufacturing studies, such as Tortorella and Fettermann (2018). Modern technologies, especially IT and digital technologies, play more and more critical roles in lean manufacturing (Pinho and Mendes 2017).

Construction learns lean techniques and tools, such as Value Stream Mapping and Six Sigma, from manufacturing. On the other hand, Last Planner represents an IT system that is specifically conceived for lean construction. Construction develops continuously. BIM is one of the most promising recent developments in the construction industry and its projects (Eastman et al. 2011). It can be defined as a process of generating and managing digital representations of physical and functional characteristics of building facilities (Tah 2012). The use of BIM can be considered as a digital revolution that enables construction to catch up with manufacturing and pursue Construction 4.0 (Dallasega, Rauch, and Linder 2018). In this research, all the interviewees believed that the use of BIM will significantly contribute to lean management in the context of construction supply chains. A consensus among the interviewees is that BIM encourages an optimal way of supply chain collaboration during a construction project. This is because BIM develops a central platform to store all available information about a building and enables all the parties who plan, design, build, operate, maintain, use and own the building to share necessary building information through the central platform. When BIM is applied in a project, a new culture is fostered in the project environment. As a result of applying BIM, better supply chain collaboration makes it more possible to improve lean construction practices.

During the interviews, several examples were provided by the interviewees to illustrate the contribution of BIM to lean construction practices, including a hospital ward and a hotel complex in the UK. BIM envisages virtual construction of building facilities. With the use of BIM in these projects, contractors could simulate construction processes prior to on-site production. As a result of virtual simulation of construction processes, non-value-adding activities were removed and meanwhile, the workflow was stabilised. On the other hand, clash detection in the BIM system is a function for virtual visualisation of building facilities, which allows designers and/or contractors to check any clashes for physical components (hard clash) and clearance spaces (soft clash) before real construction starts. In these projects, clash detection minimised the risk of human errors during design. It also avoided many problems caused by clashes, such as change orders, disruptions and rework, during construction. Consequently, clash-free design and construction made these projects leaner and more robust.

Table 5. Main findings of interviews.

	Finding
Support to the findings from questionnaire analysis	Lean construction should integrate with supply chain collaboration
New insight	Lean construction contributes to the improvement of project performance
	Industrialisation and standardisation promote the adoption of lean construction
	Not only residential buildings, many other types of projects can also apply lean construction
	ECI is important for maximising value and minimising waste that characterise lean construction
	The increasing use of BIM brings a revolution to supply chain collaboration and lean construction

Based on the integration of lean and BIM, these projects achieved significant success in terms of early completion and cost reduction to different extents. The quality of these projects exceeded the expectation of their customers.

On one hand, the interviews in this research support the findings from the questionnaire analysis. On the other hand, the interviews provide some new insights into lean construction. The main findings of the interviews are summarised in Table 5.

## 6. Conclusion

This research explores lean management in the context of project-based construction supply chains through a thorough investigation in the UK construction industry. It is found in this research that, learning from manufacturing, construction is increasingly embracing the lean concept and methodology. Going beyond the scope of existing studies that mainly focus lean construction on residential building projects, this research provides clear evidence for the implementation of lean principles in different types of projects, such as residential, educational, medical and commercial building projects as well as civil engineering projects. As a result, it is possible to gain wider popularity of lean construction. On the other hand, this research reveals that construction is increasingly infusing supply chain management into lean practices. This is because lean construction is more effective if it integrates with supply chain collaboration, especially with long-term collaboration. In other words, supply chain collaboration facilitates lean construction and accelerates lean transformation.

This research discovers an extension of lean manufacturing and a diversion from lean manufacturing as two main patterns of lean construction development. The two patterns coexist in the construction industry today. On one hand, the increasing adoption of industrialised and standardised production and the growing integration of lean construction and supply chain management can be considered as two results of construction imitating lean manufacturing. On the other hand, Last Planner, BIM and ECI can be taken as three examples to illustrate lean practices with construction-specific characteristics. The coexistence of the two patterns found in this research puts an end to the debate within previous studies about how to implement lean thinking appropriately in construction. The essence of lean thinking is value maximisation and waste minimisation. The finding suggests that both learning from other industries and pursuing own paths are indispensable for the construction industry and its projects to maximise value and minimise waste.

Unlike existing studies that mainly focus lean construction on individual case projects, this research demonstrates the significant impact of lean management on project performance based on a large number of the surveyed projects. It is found in this research that time, cost and quality performance are all significantly influenced by lean construction. Compared to time and quality performance, lean construction has a greater impact on cost performance. Undoubtedly, the implementation of lean principles plays a critical role in improving project performance and ensuring project success. The finding explains why lean construction is increasingly rooted in the context of project-based construction supply chains. The significant impact of lean construction on project performance can be interpreted as a contribution of this research to the body of knowledge. It provides organisations and practitioners with more confidence to widespread lean thinking in the construction industry.

Every study has limitations, and this research is certainly no exception. The number of questionnaire responses for government buildings, sport buildings, military buildings, industrial buildings and so on is limited. As a result, they have to be treated as other building projects in a collective way. For this reason, further research is recommended to collect more empirical information. If the sample size of the questionnaire survey becomes larger, it will be better able to compare lean construction between different types of projects. On the other hand, this research is based on the UK construction industry and therefore it has a contextual limitation. Whether the findings of this research are suitable for the global context

needs further investigation. If empirical information about lean construction can be collected from different countries, a comparative analysis will make it possible to achieve a better understanding of lean construction in different construction contexts.

### Disclosure statement

No potential conflict of interest was reported by the author.

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**Appendix 1: Sample questionnaire**

**1. Respondent information**

**1.1 What is the nature of your organization?**

- Project client
- Design team
- Main contractor
- Specialist contractor/subcontractor
- Labor, materials and equipment supplier
- Others, please specify

**1.2 What is your position in the organization?**

- General director
- Head of department
- Project manager
- Supply chain manager
- Lean manager
- Others, please specify

**1.3 How many years of work experience do you have?**

- years of experience in project management
- years of experience in lean management

**2. Project information**

**2.1 What type of project did you participate in?**

- Residential building
- University/school building
- Hospital building
- Commercial building
- Other buildings, please specify
- Civil engineering projects, please specify

**2.2 What was supply chain relationship in the project?**

- Non-collaboration
- Short-term collaboration
- Long-term collaboration

**3. Lean management**

Please rate the level of lean management during the project by selecting Very Positive (VP), Positive (P), Negative (N) or Very Negative (VN).

	VP	P	N	VN
Emphasis was placed on customer value.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Effort was dedicated to waste minimization.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Learning and innovation were encouraged.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Improvement was made continuously.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

**4. Project performance****4.1 What was the project duration?** months**4.2 Was the project completed within schedule?** Yes No, delayed by  months**4.3 What was the project budget?** million pounds**4.4 Was the project completed within budget?** Yes No, overspent by  million pounds**4.5 What was the condition of the project with respect to defect at the time of handover?** Zero or minor defect Defect with some impact Major defect Not fit for occupation