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LEAN, AUTOMATION AND MODULARIZATION IN CONSTRUCTION

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ABSTRACT

The architecture, engineering and construction (AEC) industry lags behind the manufacturing industry, both in terms of innovation and productivity, mainly due to its heterogeneous, fragmented nature and the uniqueness of its projects. This paper analyzes three effective processes and technologies which are carrying out great benefits to the construction industry: lean construction, automation, and modularization (LAM). The research consists of a systematic literature review and assesses previously published work related to the three combined topics LAM in construction with two main goals: (1) identify the relevance of the three topics combined for both the AEC industry and the academy, and (2) identify in the papers investigated the main themes related to the combination of LAM in construction. Findings reveal only 31 publications meeting the criteria within the two sources investigated. The most frequent areas of LAM identified in the papers were lean production management, optimization algorithm and prefabrication, respectively related to lean construction, automation in construction and modular construction. The results reveal a need to better investigate the interactions of LAM in construction as a way to promote the continuous improvement of the AEC industry.

KEYWORDS

Lean construction, automation, modularization, off-site construction, continuous improvement.

INTRODUCTION

Over the last decades the productivity of the architecture, engineering and construction (AEC) industry has stagnated at low levels, with no sign of improvement, as opposed to several other industry sectors, such as manufacturing or the automotive industry (McKinsey Global Institute 2017). During the same time, many concepts, technologies, systems and materials have been introduced to the industry, but performance has not increased at the expected level (World Economic Forum 2016). Research suggest that this fact is due to two main reasons: the historical resistance of the AEC industry to embrace innovation into its traditional processes, and the lack of a holistic view to address the

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problems identified in this fragmented sector (McKinsey Global Institute 2017; World Economic Forum 2016).

When applied to the AEC industry as a holistic system, the effectiveness of strategies involving lean construction, automated technologies and modular building systems has been confirmed by research (Altaf et al. 2018; Tillmann et al. 2015). Individually, each of these strategies aims to increase the productivity and quality of the construction industry. However, to this date, there is a lack of research to evaluate how those three strategies combined can boost the overall performance of the AEC industry.

INTERACTIONS BETWEEN LEAN CONCEPTS, AUTOMATION, AND MODULARIZATION IN THE AEC INDUSTRY

The industrialization of the AEC industry, involving modular construction strategies and automated process have the potential to dramatically increase productivity in the construction industry (Jensen et al. 2012). As in other industrial sectors, industrialized construction processes build on some important concepts: (1) production planning and control; (2) mechanization and automation of production processes, and (3) standardization or products and processes. These three concepts are closely related to lean construction, automation in construction, and modular construction, respectively.

Thinking of a construction project as a temporary production system, the goal of lean construction (LC) is to deliver a quality product built on value maximization and waste minimization, which means quality and productivity improvement (McGraw Hill Construction 2013). In fact, three key concepts are important to better understand lean constructions: value, flow and pull (Ballard and Howell 2003). In LC the meaning of "value" is not only cost, but mainly the customers' satisfaction. Flow refers to the movement of information and materials through all professionals involved with the project, including the production crews as well. Pull is related to planning techniques that control the flow of information and materials in a collaborative way, constantly monitoring the project schedule (Ballard and Howell 2003; Koskela et al. 2002). It is important to emphasize that construction in lean construction refers to the entire design and construction process and not only to the construction phase, as defined in the transformation-flow-value (TFV) theory (Koskela 2000).

The goal of automation is to reduce time, cost and human induced error in production processes, therefore, similarly to the lean concepts, automation should result in enhanced quality and productivity. Considering the AEC industry, automation can greatly enhance the design, construction, operation and maintenance processes of buildings. However, the construction industry is still reluctant to adopt new automation technologies capable of boosting its productivity, enhancing quality of its products and streamlining its project management procedures (McKinsey Global Institute 2017). Robotics applications, BIM tools, automated assembly lines of prefabricated modules, 4D simulations for planning and scheduling and laser scanning are some examples of important technologies whose use in AEC industry could be much more significant.

Modularization in construction is closely related to prefabrication because the modules are prefabricated, i.e. manufactured under controlled factory conditions, which assures better quality products, and more efficiency in processes and resources use. (McGraw-Hill

Construction, 2011; McKinsey Global Institute, 2017). Modular buildings can bring together the advantages of both standardization and customization, as a result of the flexible use of standardized modules combined in various ways. Research suggests that breaking down complex systems into smaller components is a good problem-solving strategy in many domains, including the AEC industry, where modules designed independently must be integrated to work together in a complex structure such as a building, considering factors such as off-site manufacturing processes, transportation and on-site assembly (Jensen et al. 2012; Sharafi et al. 2017). Thus, modularization must also be closely linked to standardization, involving a holistic standardized production process to reduce not only the variability of each module, but also the complexity of the control processes.

Individually, the areas related to LAM in the AEC industry have been extensively researched in recent years. However, to date, there is little research dedicated to analyzing the relationships between these three areas at the same time. This study will provide an overview of the main topics related to the combination of lean, automation and modular construction that have been published in the last years and which topics are the most relevant ones.

METHODOLOGY

Our purpose is to explore, through a systematic literature review, the interactions between three effective processes and technologies applied to the construction industry which are carrying out great benefits to the sector: lean construction, automation in construction, and modular construction. That said, we address the following research questions:

- How much attention has the academy and the AEC industry devoted to the study of the combined topics lean construction, automation in construction and modular construction?
- What are the most relevant issues presented on publications that simultaneously investigate the topics related to lean, automation and modularization in construction?

DATA COLLECTION AND DATA ANALYSIS

This study examines relevant papers which simultaneously analyze the topics related to LAM in the AEC industry between the years 2000 and 2018.

First, the researchers defined the terms associated to lean, automation and modularization in construction which should be used as keywords in the data selection and data analysis. The lean construction terms were defined according to Koskela's (2000) concepts of transformation, flow and value. The terms associated to automation and modularization in construction were also identified based on the literature. The main keywords identified are: (1) lean – continuous improvement, elimination waste, generation of value, optimization of process, last planner system, flow, lead time, just in time, JIT, six sigma, etc.; (2) automation: RFID (and related terms), BIM (and related terms), robotics (and related terms), sensing, algorithm, simulation, parameterization, etc.; (3) modular construction – modular, module, prefabrication, precast, parametric design, etc.

The two sources selected to collect papers were the Automation in Construction (AIC) international research journal and the International Group for Lean Construction (IGLC) website. By considering these two contrasting sources of data, the study allows for a good overview of the current scenario of published papers that simultaneously cover the topics LAM in construction.

A total of 326 papers were retrieved from the AIC and IGLC websites using the following search criteria:

Automation in Construction – returned a total of 240 papers.

- Years: 2000-2018 (from January to December, including papers available online before published).
- Article type: review articles and research articles.
- Keywords: lean, modular building, modular construction, prefabrication, prefabrication AND lean, prefabrication AND modular.

International Group for Lean Construction – returned a total of 86 conference papers.

- Years: 2000-2018 (from January to December)
- Keywords: automated, automation, BIM, modular, prefab.

The selected papers were imported into NVivo and text mining queries were performed as follows (parameters – no spread and grouping with stemmed words):

- Considering that all the 86 papers from the IGLC are related to lean in construction, the researchers ran multiple text search queries using the keywords related to automation and modularization. After eliminating the duplicated papers, the content of each paper was manually assessed by the first author, who first looked for the defined keywords in the Title, Abstract and Keywords of each paper and then, if the related terms were not identified, the researcher assessed the full content of the paper. As a result of this process, a total of 12 papers with the joint content on LAM in construction were selected.
- Considering that all the 240 papers from the AIC are related to automation in construction, the researchers ran text search queries using the keywords related to lean construction and modularization. Here again the content of each paper was manually assessed, resulting in 19 papers with the joint content on lean, automation and modularization in construction.

A total of 31 papers addressing lean, automation and modularization in construction resulted from this selection.

Following, aided by NVivo and based on the defined keywords, the first author manually identified the topics of each paper related to LAM in construction. Based on the thematic analysis method (Braun and Clarke 2009), the researcher identified the themes emerging from the papers. The papers were then clustered by lean construction themes, based on the transformation-flow-value theory (Koskela 2000) and in the value, flow and pull concepts defined by Ballard and Howell (2003).

RESULTS AND DISCUSSION

Results from our research indicate that in recent years, especially in 2018, AIC has published a growing number of papers that cover all three LAM topics – lean, automation and modular construction (Figure 1). However, for the IGLC the number of papers published that satisfy this criterion was more expressive in 2015 and have stabilized since 2017 with a couple per year (Figure 2).

The relation between the total number of papers published and the number of papers addressing the combined topic LAM in construction suggests a low degree of interest from both research and practice in exploring the interactions of LAM in construction. For example, the following numbers present the proportion of LAM papers that were published by AIC and IGLC in 2018:

- AIC magazine: in 2018 (Jan-Dec), 6 out of 313 (1.92%) published papers addressed the combined topic LAM in construction.
- IGLC website: in 2018 (Conference IGLC 26 - Chennai, India), 2 out of 134 (1.49%) published papers addressed the combined topic LAM in construction.

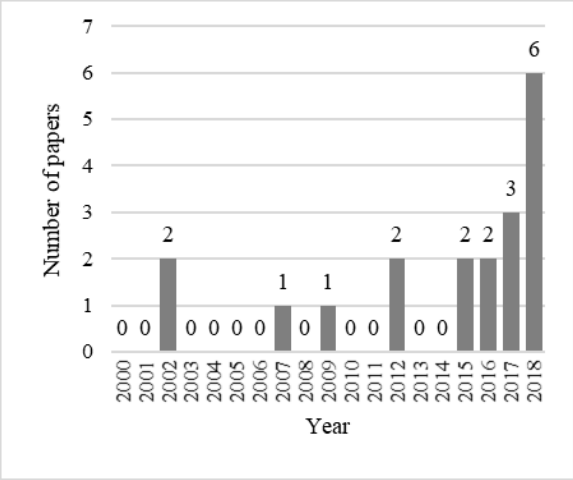

Figure 1: AIC LAM papers (n=19)

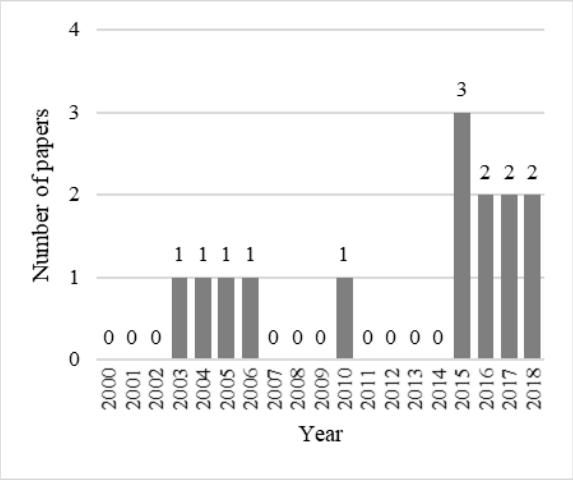

Figure 2: IGLC LAM papers (n=12)

The topics related to LAM in construction, grouped by lean construction themes are presented in Table 1, with the most frequent topics related to lean construction, automation and modularization in construction shaded in grey.

Table 1: Main topics related to lean, automation and modularization in construction

Author	Lean Construction Topics	Automation in Construction Topics	Modular Construction Topics
LC Theme: Lean Management			
Altaf et al. 2018	Production planning and control	RFID, RANSAC model optimization algorithm	Panelized wall production facility for prefabricated homes
Arashpour et al. 2015a	Production planning and control	Autonomous production tracking	Off-site construction plant: precast concrete tanks

Author	Lean Construction Topics	Automation in Construction Topics	Modular Construction Topics
Bataglin et al. 2017	Logistics planning and control	4D BIM modelling	Logistics: Engineer-to-order (ETO) concrete prefabricated structures
Bortolini et al. 2015	Logistics planning and control: in construction sites	4D BIM modelling	Logistics: ETO prefabricated building systems
Gerber et al. 2010	Lean construction principles: look ahead planning, design and construction integration	BIM: fabrication processes, design and construction integration	Prefabricated components: various
Murphy et al. 2018	Lean construction principles: predictability	VDC methods and Reality Capture	Prefabrication: interior wall panels
Peñaloza et al. 2016	Integrated production control	4D BIM: physical flows, control of assembly process	ETO prefabricated concrete systems
Cheng and Chen 2002	Controlling and monitoring construction progress	Automated schedule monitoring system	Precast building construction
Sacks et al 2003	Lean production and delivery: monitoring	Real-time automatically monitoring & 3D modelling	ETO: precast concrete pieces
Tillmann et al. 2015	Lean principles: lead time, production planning and control	BIM: integrated management	ETO components
Zhong et al., 2017	Monitoring: visibility and traceability in manufacturing, logistics and on-site assembly	Internet-of-Things & BIM real-time automated monitoring	Prefabricated construction: manufacturing, logistics and on-site assembly
Arashpour et al. 2016	Scheduling: resource sharing and job sequencing	Optimization modeling algorithm	Off-site construction plant of concrete panels
Kong et al. 2017	Scheduling: cost and time constraints integrating manufacture, transportation and on-site assembly (JIT)	Dynamic programming algorithm: maximum production efficiency	Precast construction: manufacturing, transport, delivery, on-site assembly
LC Theme: Flow – Increase Flexibility			
Arashpour et al. 2015	Multi-skilled resources: flexibility, process integration	Optimization modeling algorithm - SIMAN code	Off-site construction plant
Arashpour et al. 2018	Process integrations and multi-skilled resources	Optimization modeling algorithm	Off-site construction plant
Isaac et al. 2016	Flexibility: product adaptability	Clustering algorithm: design graph-based analysis	Modularization of building design
LC Theme: Waste Elimination (non-value-adding activities)			
Banihashemi et al. 2018	Waste reduction workflow	Generative algorithm and Modular coordination	Parametric design and modular coordination integration
Cheng et al. 2015	Waste reduction: construction and demolition	BIM: automated quantity take-off, planning, design reviews, clash detection and digital fabrication	Digital prefabrication
Yuan et al. 2018	Lean construction: simplify design, manufacture and assembly to reduce time and costs	Design for Manufacture and Assembly-oriented parametric design with BIM	Prefabricated building design, parametric components, precast components

Author	Lean Construction Topics	Automation in Construction Topics	Modular Construction Topics
LC Theme: Lean layout			
Chen et al. 2018	Facility layout planning: minimize production time and maximize workstation use	Automated guided vehicle-based flow production system and genetic algorithm	Precast factory layout: modular prefabricated manufacturing system
Cheung et al. 2002	Site precast yard layout to minimize transport cost	Genetic algorithm model	Precast: on site layout arrangement
Nasereddin et al. 2007	Lean construction: factory more flexible, responsive, and efficient	Automated modeling	Modular home manufacturing industry
LC Theme: Pull System – Controlling Resources Flow			
Liu and Lu 2017	Supply chain management	Constraint programming-based optimization algorithm	Supply chain and module assembly plan
Chin et al. 2004	Supply chain management	RFID: product and information flow management	Supply chain: curtain walls
Tiwari et al. 2018	Supply chain management and job sequencing	BIM: real-time sequencing and digital fabrication	Supply chain: light gauge metal stud panels
LC Theme: Visual Management – Transparency			
Han et al. 2012	Lean production: Value Stream Mapping (VSM)	Automated post-simulation visualization	Modular building production line
LC Theme: Value – Customer Satisfaction (Quality, Cost and Time)			
Benros and Duarte 2009	Customer satisfaction and mass customization	Automated production	Mass customized housing, prefab building system
Said et al. 2017	Flexibility and customer value: mass customization and platform design	Algorithm: platform design optimization	Mass customization: exterior panelized walls, module design for prefabrication,
Jensen et al. 2012	Customization: flow of information - customer/engineer/ production	Design automation: CAD and manufacturing CAD tools	Parameterization of building components and customization
LC Theme: Miscellaneous			
Pasquire et al. 2006	Lean construction principles	Digital construction	Digital Prefabrication
Xu et al. 2018	Lean construction: service-sharing platform	Integrated cloud-based IoT platform	Prefabricated construction: production, logistics and on-site assembly

A summary of the most frequent themes related to lean construction, automation and modularization in construction found by the thematic analysis is presented as follows:

Lean Construction:

- Lean Management – 11 papers. Related topics: planning, control, scheduling, monitoring, predictability, etc. Related terms: production, supply chain, logistics, multi-skilled resources, time, cost, process integration, resources, etc.)

Automation in Construction:

- Optimization Algorithm – 11 papers. Related topics: programming algorithm, genetic algorithm, generative algorithm, clustering algorithm, etc. Related terms: programming, modelling, constraint programming, etc.

Modularization in Construction:

- Prefabrication – 9 papers. Related topics: prefabricated construction, prefabricated building design, digital prefabrication, precast components, etc. Related terms: manufacturing, logistics, assembly, parametric design, etc.

Following, we discuss how the lean construction theme – Lean Management – connects to automation and modularization themes in the AEC industry domain.

INTERACTIONS OF LEAN MANAGEMENT WITH AUTOMATION AND MODULARIZATION IN CONSTRUCTION THEMES

Lean Construction Theme: Lean Management

Lean Management encompasses planning (Lean Work Structuring – LWS) and control (Last Planner System – LPS). Considering the papers analysed and the lean construction concepts (Koskela 2000; Koskela et al. 2002), LWS and LPS purposes are: (1) design and plan the whole construction process – manufacturing, transport and assembly; (2) identify repetitive processes; (3) implement standard process; (3) stablish collaborative schedules (pull scheduling); (4) define work plans; (5) eliminate workflow variability; (6) monitor productivity evolution; (7) actively control the workflow; (8) improve performance – increase value.

According to previous research these goals are built on solid collaboration among the project stakeholders and constant monitoring and control, which fosters a sense of teamwork and transparency (Koskela 2000; Koskela et al. 2002).

Automation and Modularization in Construction Themes

The papers grouped under the lean management theme were clustered in four themes related to automation in construction: (1) algorithm; (2) BIM; (3) automated monitoring and tracking systems; and (4) virtual design and construction (VDC).

As for the modularization in construction themes, we have: (1) off-site construction facilities; (2) prefabrication; and (3) engineered-to-order (ETO) components.

Two papers discussed how algorithms can automate production processes, optimizing planning, control and scheduling in off-site construction facilities. The solution implemented in a prefabricated homes factory is based on an optimization algorithm which enables real-time scheduling and performance monitoring using the production data collected by radio frequency identification (RFID), whose noisy is automatically removed by a RANSAC model before being used in a simulation model and then, integrated with the optimization algorithm (Altaf et al. 2018). The other paper uses an optimization modelling algorithm to define the optimal product sequencing considering resource sharing and job sequencing for a concrete panels factory (Arashpour et al. 2016). Algorithm enhancing lean construction was also explored by Kong et al. (2017), who presents a dynamic algorithm that optimize scheduling for manufacturing, transportation and assembly of precast construction.

Prefabrication theme has many synergies with lean construction and BIM. BIM allows for automating many processes in the AEC industry, such as: drawing review, design

coordination, scheduling, cost control, work monitoring, etc. In addition, BIM is paramount for automating construction processes by using robots and CNC process. The two papers addressing prefabrication and lean management interactions use BIM strategies to implement lean principles in the construction processes. BIM is used to automate fabrication processes, enhance design and construction integration and enable look ahead planning in projects using precast components for façades (Gerber et al. 2010). The internet of things (IoT) and BIM are presented as enablers of prefabrication process and lean management by automatically monitoring the manufacturing, logistics and on-site assembly processes (Zhong et al. 2017).

BIM and engineered-to-order (ETO) components interactions are discussed in five papers. 4D BIM modelling is used for planning and control logistics operations in ETO prefabricated building components (Bataglin et al. 2017; Bortolini et al. 2015). Integrated production control (design, manufacturing and assembly) in ETO prefabricated concrete building systems is automatically enabled by 4D BIM simulations (Peñaloza et al. 2016). The use of lean principles in the design-production interface of ETO components is presented as a means of leveraging BIM, which is used as support to management practices (Tillmann et al. 2015). Engineered-to-order (ETO) components synergies with lean management are enhanced by using 3D modelling and real-time monitoring (Sacks et al. 2003).

An automated schedule monitoring system enhances control and monitoring of precast building construction progress by integrating Geographic Information System (GIS) with a database management system (Cheng and Chen 2002). An autonomous production tracking mechanism for production management enables real-time scheduling updates (Arashpour et al. 2015a).

Finally, virtual design and construction (VDC) methods and reality capture technology are presented as a means to enhance design coordination, increase the predictability and provide feedback for site conditions in prefabricated wall panel design process (Murphy et al. 2018).

CONCLUSIONS

This study investigated the relevance of the combined topics lean, automation and modularization (LAM) in construction for research and practice. The authors performed a systematic literature review on papers from two sources, AIC journal and IGLC website, between 2000 and 2018. Results revealed a low number of papers (n=31) approaching all LAM topics combined. In addition, published work connecting the three topics under analysis were found to be mainly focused on the following themes: (1) Lean construction – lean production management; (2) Automation in construction – optimization Algorithm; (3) Modularization in construction – prefabrication. The results reveal the existence of great research potential exploring the interactions of the set lean practices, automation and modularization in the AEC industry, as a way to enhance the industry performance and engage it in a process of continuous improvement.

The limitations of this study are related to the exploratory nature of this research and related to: (1) only using published papers from two sources; (2) findings were limited to the keywords used in the process of paper selection; and (3) the thematic analysis was

carried out by only one researcher. An expanded research, considering published work from a larger number of academic sources, different keywords used to select the papers and two researchers working the thematic analysis is under way and may reveal a slightly different picture or confirm what was found in this study.

Recommendations for future research on the interactions of lean, automation and modularization in the AEC industry would include assess topics that are gaining more relevance in today's construction scenario – such as robotics (automation), integrated project delivery (lean), and parameterization of modules (modularization) – and the results of possible combinations of these topics for the AEC industry improvement.

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