
# A review on the interactions of robotic systems and lean principles in offsite construction



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# A review on the interactions of robotic systems and lean principles in offsite construction

## Abstract

**Purpose** – The purpose is two-fold: (1) to explore the interactions of robotic systems and lean construction in the context of offsite construction (OC) that were addressed in the literature published between 2008 and 2019 and (2) to identify the gaps in such interactions while discussing how addressing those gaps can benefit not only OC but the AEC industry as a whole.

**Design/methodology/approach** – First, a systematic literature review (SLR) identified journal papers addressing the interactions of automation and lean in OC. Then, the researchers focused the analysis on the under-researched subtopic of robotic systems. The focused analysis includes discussing the interactions identified in the SLR through a matrix of interactions and utilizing literature beyond the previously identified articles for future research directions on robotic systems and lean construction in OC.

**Findings** – The study found 35 journal papers that addressed automation and lean in the context of OC. Most of the identified literature focused on interactions of BIM and lean construction, while only 9 focused on the interactions of robotic systems and lean construction. Identified literature related to robotic systems mainly addressed robots and automated equipment. Additional interactions were identified in the realm of wearable devices, unmanned aerial vehicles/ automated guided vehicles, and digital fabrication/CNC machines.

**Originality** – This is one of the first studies dedicated to exploring the interactions of robotic systems and lean construction in OC. Also, it proposes a categorization for construction automation and a matrix of interactions between construction automation and lean construction.

**Keywords** Offsite construction; Construction automation; Lean construction; Robotic systems; Systematic literature review

**Paper Type** Literature Review

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# 1. Introduction

The architecture, engineering, and construction (AEC) industry has been experiencing low levels of productivity over the years, even with the gradual introduction of several new technologies and processes (McKinsey Global Institute, 2017). Many factors contributed to this situation, especially a historical resistance of the AEC industry to embrace innovation and industrialization into its traditional processes (Linner and Bock, 2012), and the lack of a holistic view to address the problems identified in this fragmented industry (World Economic Forum and The Boston Consulting Group, 2016).

At the company level, practices to improve the AEC productivity involve technologies and tools, processes and operations, business models, and human resources and organizations (World Economic Forum and The Boston Consulting Group, 2016). Aligned with these practices, three concepts stand out: offsite construction (OC), construction automation (CA), and lean construction (LC). Technology-driven construction companies such as Katerra, Factory_OS, and Prescient are revolutionizing the AEC industry by providing practical examples of the combined application of OC, CA, and LC (Ponsor and Cohen, 2019).

Despite a growing interest from industry, to date there are few holistic academic studies on the interactions of CA and LC within the context of OC. This is an important topic, as this type of analysis can provide a better understanding of the benefits that such interactions can bring to the AEC industry comparing to the studies of CA and LC in isolation. Individually, CA, LC, and OC have attracted the attention of both academia and industry (McGraw Hill Construction, 2013; McKinsey Global Institute, 2017). Significant research has also addressed the interactions between LC and CA (Dave et al., 2016; Hamzeh et al., 2015; Sacks et al., 2010), LC and OC (Nahmens and Ikuma, 2012; Yu et al., 2013), and CA and OC (Jaillon and Poon, 2014; Salama et al., 2017). Research suggests that the strategies involving the integrated adoption of OC, CA, and LC are effective to tackle the factors that are hindering the AEC industry progress than their individual contributions, justifying a deeper investigation on the interactions between them (Altaf et al., 2018; Linner and Bock, 2012; World Economic Forum and The Boston Consulting Group, 2016; Zhong et al., 2017).

Through a systematic review of the literature, this article identifies and maps out the reported interactions of CA and LC in the context of OC. As CA is a very comprehensive topic and given the limitations of this paper, the focus of this study is on exploring and improving the understanding of the interactions between lean construction and a specific category of CA, namely robotic systems (RSs), since such interactions have been scarcely explored in the literature so far. In addition, the high similarity between OC processes and manufacturing processes facilitates the implementation of RSs and LC principles to increase efficiency and productivity in offsite construction (Martinez et al., 2008; Martínez et al., 2013). Once the interactions of RSs and LC found in the literature are mapped out and explained, the research gaps are also identified and subsequently discussed, resulting in a roadmap for future research. In addition to the contributions to the academic community, the list of potential benefits resulting from the joint adoption of LC and RSs for both offsite construction and the broader context of the AEC industry constitute an important contribution to the practice.

## 2. Background

Automation technologies and lean principles have been widely and successfully applied to many industries such as the automotive and the manufacturing industries (Kolberg and Zühlke, 2015). Expanding on other industries' experiences, the enhancement of the AEC industry involving OC, CA, and LC has the potential to dramatically increase the productivity and efficiency in construction (Jensen et al., 2012; Linner and Bock, 2012; World Economic Forum and The Boston Consulting Group, 2016). Based on the experience from other industries, the integrated adoption of CA, LC, and OC by the AEC industry can improve the construction sector by using: (1) innovative tools and technologies to automate and speed up the production processes, (2) efficient management systems to control the production, and (3) an environment conducive to industrialization of production. Figure 1 illustrates how CA, OC, and LC principles can be applied to the AEC industry.

**<Insert Figure 1 here>**

Figure 1. Theoretical Framework

### *2.1. Offsite construction (OC)*

Offsite construction (OC) refers to the manufacturing and pre-assembling of construction components in a manufacturing site, which are then transported and assembled on the construction-site (Goodier and Gibb, 2007). OC can be categorized according to the type of element and the level of offsite work undertaken on the building (Gibb, 2001).

Depending on the level of adoption of offsite construction in a project, different strategies are necessary throughout the construction process, which will have different impacts and will need to be properly analyzed in each phase, from the design to the completion of the building.

Currently, OC is again gaining ground in the AEC industry, greatly driven by the rise of lean construction (McGraw Hill Construction, 2013) and Building Information Modeling (BIM) (Teicholz, 2014). In fact, OC has been increasingly recognized as one of the most effective methods to achieve lean construction (Xu et al., 2018). The AEC industry has reported many challenges associated with the adoption of OC, including the need to commit to a well-defined design and engineering work at an early stage of the project and the complex transportation and logistical requirements involved in the process of shipping components to the site (McGraw-Hill Construction, 2011; McKinsey Global Institute, 2017). However, owners, designers, and contractors have also acknowledged productivity improvements such as cost and time reduction and safety improvement (McGraw-Hill Construction, 2011).

### *2.2. Construction automation (CA)*

Construction automation (CA) is defined as the use of technologies to improve productivity, safety, scheduling, control, or constructability, and serves as a tool to assist in the decision making process of project stakeholders (Castro-Lacouture, 2009). CA can enhance design, construction, and operation processes, positively impacting the entire lifecycle of buildings (Eastman et al., 2008).

Some challenges to a wider use of CA include cost, regulatory restrictions (Castro-Lacouture, 2009), deficiencies in information usage, investment from companies (Chen et al., 2018), changes in the workforce, cybersecurity awareness (Soto and Skibniewski, 2020), and the interactions of workers and automation technologies (Afsari et al., 2018). Despites these challenges, some technologies related to CA, such as robotics and BIM, are gaining traction (Sawhney et al., 2020). The main motivations to automate include productivity, safety, quality, and economy improvements, which are all linked to lean concepts (Nof, 2009).

As construction automation covers a wide range of applications and technologies, it is important to define which technologies are grouped under this umbrella. The analysis of relevant and recent literature focused on emerging technologies and trends (Davila Delgado et al., 2019; Gerber et al., 2017; Meng et al., 2020; Nof, 2009; Oesterreich and Teuteberg, 2016; Saidi et al., 2016; Sawhney et al., 2020) allowed the authors to categorize construction automation according to the technologies presented in Table I.

Table I. Construction Automation Technologies

**<Insert Table I here >**

The five main technologies encompassed by construction automation, namely (1) Robotic Systems, (2) Modeling and Simulation, (3) Digitization and Virtualization, (4) Sensing Systems, and (5) Artificial Intelligent and Machine Learning are briefly described below.

1. Robotic systems include advanced construction equipment with capabilities related to teleoperation and autonomous task performance (Sawhney et al., 2020). In this study, robotic systems comprise robots, automated equipment, digital fabrication machines, UAVs and AGS, and wearable devices. The use of robotic systems is ideal for large-scale offsite production of prefabricated components using gantry robots, fixed robotic arms, collaborative robots, 3D printers, AGVs, and even drones to monitor inventories. However, some types of robotic technologies are suitable for tasks on the construction site: on-site factories, single task robots, automated equipment (cranes, excavators, etc.), monitoring robots and UAVs, and exoskeletons (Davila Delgado et al., 2019).

2. Modeling involves digital representations of physical and functional characteristics of real-world products and processes (Sacks, Koskela, et al., 2010). Technologies under this category include BIM models (3D, 4D, and 5D), which contain different levels of information needed to complete a construction project and are used throughout the life cycle of that project (Eastman et al., 2008; Sacks, Koskela, et al., 2010). VR is also a digital representation of the real world, while AR and MR combine digital content on the real-world environment. However, MR is more immersive and interactive than AR. Simulations are used to analyze the performance of the modeled products and processes. Computer simulations in construction are used to predict the potential effects of events

or processes, support decision-making, develop feasibility studies, and model and plan production processes (Han et al., 2012).

3. Digitization and virtualization are processes related to the concept of Industry 4.0 and digital transformation which are now being applied in the AEC industry. Digitization is a term related to the extensive use of Information and Communications Technology (ICT) to create a digital representation, that is, to transform information into a digital format (Oesterreich and Teuteberg, 2016). Focusing on digital project data and information management, digitization and virtualization include (1) enterprise information system (EIS) to integrate information throughout a project, (2) cloud computing and digital platforms, (3) Internet of Things (IoT) platforms to digitize physical products, and (4) big data to capture, store, analyze, and manage large data sets.
4. Sensing technologies involve the use of sensors. A sensor is “a device that receives a stimulus and responds with an electrical signal” (Fraden, 2016). RFID, for example, has been used at various stages of construction: from production to logistics and on-site operations, consisting of tracking workers, equipment and components, which allows the representation of the physical condition of the logistic/ production flow in real-time and in an informative way (Altaf et al., 2018; Wang et al., 2017). In addition, sensing technologies are useful for automated construction progress monitoring when associated with the use of images and videos.
5. Artificial Intelligence (AI) is the study of computational processes to allow perception, reasoning, and action (Winston, 1992), while machine learn (ML) enables the computer to learn from experience. Recently, there has been growing interest in the application of AI and ML in the AEC industry to automate the design process, cost estimation, and construction safety monitoring. For instance, genetic algorithms, neural networks, and expert systems have been used in preconstruction planning to automatically estimate the project duration, generate the work breakdown structure, and optimize resources (Faghihi et al., 2015).

### *2.3. Lean construction (LC)*

Lean production principles were initially applied in the manufacturing industry, but as other industries recognized the potential benefits of the lean principles, they started to adapt and apply them to improve their processes (Koskela, 2000). In construction, lean “is a way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value” (Koskela et al., 2002). In lean construction (LC), the term construction refers to the entire lifecycle, from conception (design) to production (construction), as defined in the transformation-flow-value (TFV) theory (Koskela, 2000). LC involves a series of principles to guide the management process. The LC principles that support this study are based on the list of lean principles defined by Sacks et al. (2010), whose study focused on the interactions of LC and BIM, which are summarized in Table II.

Table II. Lean Principles

**<Insert Table II here>**

The practical application of the LC principles comprehend numerous practices and techniques such as just-in-time, last planner system, six sigma, and pull planning, which are related to (1) design and engineering, (2) planning and control, (3) construction and site management, and (4) health and safety management (Babalola et al., 2019). Research has revealed many benefits associated with the implementation of LC practices, most notably, the reduction of project duration (Erol et al., 2017), cost (Nowotarski et al., 2016), and waste (Tezel and Nielsen, 2013), and the improvement of quality (Sarhan et al., 2017), productivity, work performance (Zhang et al., 2018), and safety (Sarhan et al., 2017). Most of the lean practices implemented in the AEC industry are related to project management, more specifically to the triple constraints (time, cost, and scope), quality, and customer relationship (Babalola et al., 2019).

## 3. Methodology

This study uses a systematic review methodology to identify and evaluate current literature relevant to the integrated use of CA and LC in the context of OC, providing an overview of the interactions between the three topics. The systematic literature review constitutes a reliable method to identify and expand the body of knowledge of a specific domain and have been used by many researchers to investigate different topics related to the AEC industry (Jin et al., 2018; Santos et al., 2017; Yin et al., 2019).

Considering that the interactions between the three topics of interest need to be investigated timely, the authors investigated the articles published between 2008 and 2019. The reasons for this time range include the increased attention of the investigated topics in recent years in academia and the fact that multiple scholars have adopted a ten year period as a typical timeline in selecting recent publications for literature review (Jin et al., 2018; Santos et al., 2017; Yin et al., 2019). Figure 2 shows the six-steps methodology used in this study.

**<Insert Figure 2 here>**

Figure 2. Methodology

### *3.1. Step 1. Article sources identification*

An initial pilot search in main databases, including Scopus, Engineering Village, and ProQuest Technology Collections, was conducted and resulted in few articles that addressed the interactions of CA and LC in OC. Therefore, the authors decided to perform searches directly in specific journals' data bases. The journals were selected based on their relevancy in the AEC domain and their measures of scientific influence according to the SCImago Journal Rank (SJR) indicators in 2017. Only journals with an SJR factor greater than 0.55 and impact index greater than 1.5 were considered, resulting in 17 selected journals.

### 3.2. Step 2. Search strategies implementation

Terms associated to OC, CA, and LC were defined and used as keywords in data selection and data analysis. The searches were conducted in the databases of each selected journal, which allowed a thorough search in the full article. Different searches strategies such as combining keywords, boolean connectors, truncates, and wildcards were used to improve the retrieval rate of related articles. The three groups of keywords used were: (1) automation, robot, BIM, CNC, laser scan; (2) prefab, modular, offsite; and (3) lean, "just in time". The searches conducted in the journal databases resulted in a collection of 460 articles.

### 3.3. Step 3. Initial assessment

A text mining analysis on the combined topics of OC, CA, and LC was performed using NVivo software. Then, a manual assessment on the abstracts and conclusions of each article was performed by two of the authors, narrowing down the results to 35 articles that addressed the interactions of CA and LC in OC.

### 3.4. Step 4. Qualitative analysis

The authors conducted a thematic analysis (Braun and Clarke, 2006) to identify the emerging themes related to the interactions of OC, CA, and LC, which were then mapped in a matrix. Through this process the authors organized the articles according to the interactions addressed in them and identified the most and least researched interactions.

### 3.5. Step 5. Data synthesis

Following, based on the number of researched interactions, the authors selected the CA category, Robotic Systems, to be further explored. By analyzing the interactions of RSs and LC supported by the investigated literature, the authors synthesized and explained them, exposing the gaps in the existing knowledge and suggesting areas of interactions that need further research in the context of OC.

### 3.6. Step 6. Inferences' support survey

The authors sought evidence in literature beyond those focused on OC – including the AEC industry in general and even research related to other industries (manufacturing, automotive, etc.) – to support the inferences on the gaps of RSs and LC interaction in the context of OC. Searches for additional supportive literature were carried out broadly, on several platforms, using terms related to LC and RSs, without focus on OC. Based on the literature gathered, the authors were able to provide evidence that justify the need to further research some of those gaps of RSs and LC interaction as a way to improve the overall performance of the AEC industry.

## 4. Results and Findings

Results from our research indicated that Automation in Construction is the journal with the highest number of articles addressing the interactions of CA and LC in OC (Table III). And considering the number of articles published by year, the findings suggested that the interactions of CA and LC in OC have received increasing attention in recent years, as 22 out of the 35 articles were published between 2017 and 2019 (Figure 3).

Table III. Number of Articles by Journal (n=35)

**<Insert Table III here>**

**<Insert Figure 3 here>**

Figure 3. Articles Published by Year (n=35)

### *4.1. Interactions between OC, CA and LC*

The interactions of CA and LC in OC for each article were identified, associated to a number, and mapped out in a matrix of interactions (Table IV), which revealed that many interactions, though significant, have not been studied. The rows of the matrix represent the CA technologies while the columns are the LC principles. Each article can have multiple interactions, depending on the topics it addresses. For example, the interactions of CA and LC in Chen et al. (2019) – assigned to number 9 – were associated to the CA category "UAS/UAV and AGV". As for LC, the article was associated to two principles, namely "Reduction of variability" and "Reduction of cycle times/inventories". This is because the study showed that the use of an AGV-based manufacturing system reduced variability and cycle time in the production of modular prefabricated components.

Table IV. Matrix of Interactions of Lean Construction Principles and Construction Automation Technologies (n=35)

**<Insert Table IV here>**

The matrix revealed that the most frequent interactions addressed in the investigated literature were focused on modeling and simulation and LC principles. For instance, just for the modeling and simulation category, a total of 15 papers concentrated on BIM. While Robotic systems (RSs), on the other hand, was the least explored topic in the investigated literature, with a total of 9 papers addressing the interactions of RSs with LC. This result was unexpected because RSs have been extensively investigated in other industries, such as the manufacturing industry, which shares many similarities with OC. In addition, the AEC industry has been affected by the labor shortages, which is one of the main drivers for the use of RSs. The use of robotics in construction has been explored in applications such as bricklaying, construction inspection, and concrete finishing. However, applications of RSs along with LC in OC is still limited. Next, the authors discuss the interactions between RS and LC found in the investigated literature. In addition, gaps on such interactions are identified and described.

### *4.2. Robotic systems (RSs) and lean principles*

The high similarity between production and assembly processes in OC and the manufacturing industry processes allows the implementation of RS and LC principles to increase the efficiency and productivity in construction (Martinez et al., 2008; Martínez et al., 2013). To illustrate this concept, Martinez et al. (2008) presented two assembly systems for modular construction: an offsite assembly system using a robotic assembly tool and an on-site mobile assembly facility, both enabled by concepts of design for manufacturing and assembly. Later, Martínez et al. (2013) refined the onsite mobile robotic system and proposed a flexible field factory for production of modular systems based on lean production principles. They showed through simulations and comparisons with traditional assembly methods that their proposed field factory allowed for greater flexibility in production and savings in assembly and transportation time and costs. Furthermore, Zhang et al (2018) explored the adoption of robotic total station devices, which are BIM enabled to lay out the hangers for prefabricated mechanical, electrical and plumbing (MEP) racks on the slabs during the construction phase. The robotic layout allowed a four-time increase in productivity related hanger installation. Zhang et al (2018)' study mostly focused on the interactions of BIM and lean principles, which not only facilitated the installation of MEP systems in the construction phase, but also reduced waste and increased value throughout the project lifecycle by improving the design coordination and the workflow, allowing for more prefabrication opportunities, reducing construction errors and rework, and increasing the confidence of work teams.

To achieve the full benefits of integrating robotics and lean principles in OC, it is necessary to consider this integration from the initial design stages, through manufacturing to on-site assembly. For this reason, the adoption of BIM technology is fundamental, as suggested by Malik, Ahmad and Al-Hussein (2019) in their proposed framework for the automated generation of tool paths from BIM to an automated cutting machine. Their framework allowed the optimization of material use through waste allocation during the cutting operations of floor components in panelized floor manufacturing. The overarching approach in the use of automated construction processes, including the adoption of robots, automated equipment, and digital fabrication tools presented by Linner and Bock (2012), also highlighted BIM as a pre-condition to higher levels of automation. Based on the Japanese housing industry model, which brought the housing construction industry closer to the manufacturing industry, their study revealed that by using superior technologies and highly efficient production methods, the Japanese housing industry offered high-quality products focused on customer relationship and value, which is one of the most important aspects of the lean philosophy.

Focusing on the use of automated equipment, Azzi et al. (2011) addressed the automation processes in an Italian company that designs, manufactures, and installs unitized curtain walls. Their study revealed the great potential of increasing productivity and production flexibility and reducing variability in the assembly of product families using optimized lean layout of assembly line and automated equipment. Innella et al. (2019) identified through a literature review, the importance of adopting autonomation and autonomous production systems in modular construction to improve the production flow and reduce variability. Similarly, Goh and Goh (2019) showed the benefits of adopting automated gantry cranes in prefabricated prefinished volumetric construction operations to achieve lean principles. The automated gantry cranes were used to pick and place modules without human supervision, which increased efficiency, reduced defective work and variability as demonstrated in the simulation model developed in their study.

In the context of OC, the manufacturing phase allows the greatest amount of interactions between RSs and LC (Linner and Bock, 2012), ranging from layout planning and installation of equipment at the manufacturing facility to studies on machinery and equipment optimization. Chen et al. (2019) proposed a facility layout planning method based on the use of an algorithm to optimize the storage area of prefabricated components in precast factories. The proposed facility layout was based on the use of automated guided vehicle and concepts from the manufacturing industry, with a special focus on decreasing queues and bottlenecks in the production process while maximizing the workstation utilization and reducing the required storage area (Chen et al., 2019).

Based on the 9 papers discussed above, which addressed the interactions of RSs and LC in OC, the authors developed a rationale for each identified interaction and related it to the investigated literature (Table V)

Table V. Interactions of RSs and LC Principles in OC Supported by the Investigated Literature

**<Insert Table V here>**

### *4.3. Future directions of research on the interactions of RSs and LC in OC*

The analysis of Table V indicates that the examined literature did not address all the potential interactions between RSs and LC in OC, hence, the authors identified research in other areas of construction (not focused on OC) or even related to other industries and domains to provide evidence on the importance that such potential interactions would likely present in the context of OC, justifying the need for further research. The results are presented in Table VI.

Table VI. Potential Interactions of RSs and LC Principles Within OC to be Further Investigated

**<Insert Table VI here>**

### *4.4. Matrix of interactions between RSs and LC in OC*

The authors summarized and presented the interactions between RSs and LC principles, as a matrix in Table VII. Each letter in the matrix stands for an interaction and may be applied to more than one RSs and LC principles. The grey cells (A through I) in the matrix refer to the interactions identified in the investigated literature related to OC (see table V). The other cells (J through Z) refer to interactions identified in literature related to construction in general, manufacturing, robotics, and even the military context (see table VI). The cells that do not hold any letters refer to the interactions that the authors considered not significant to be explored.

Table VII. Matrix of Interactions Between RSs and LC Principles

**<Insert Table VII here>**

The interactions of RSs and lean principles are more noteworthy in the manufacturing and on-site construction phases of OC, but they bring contributions to enhance the design phase, since all RSs can be integrated with BIM tools to provide feedback on problems that need to be solved in the early stages of a project. It is important to note that some of the interactions discussed help to support a more intense use of OC by the AEC industry because (1) they are only possible within the context of OC, as they only apply to the manufacturing phase – see interactions C, N, and P, or (2) they apply to the construction phase, but are much more significant in the manufacturing phase – see interactions L and O.

## 5. Conclusions

In this study, the authors analyzed the interactions between CA and LC in the context of OC through a systematic literature review. The integration of CA and LC in OC provides means to enhance the AEC industry practice (e.g., increase productivity and reduce waste). This study investigated articles published between 2008 and 2019 focused on the interactions of CA and LC in OC. All the interactions identified were mapped out in a matrix, which allowed to visualize the interactions that have attracted more attention in the literature and the interactions that, although important, need to be further investigated.

The results indicated a lack of research on the interaction of RSs and LC. Hence, the study discussed the potential interactions between RSs and LC in OC and created another matrix to map out them, showing all the interactions identified in the systematic literature review and the interactions that are worth to be further explored. Based on the systematic review, within the context of RSs, the two most explored subcategories in terms of interactions with LC were robots (e.g., industrial arms) and automated equipment. The implementation of these technologies associated with LC principles provides benefits in terms of quality, schedule and cost, including reduction of variability in the manufacturing of the prefabricated components (higher quality), reduction of production cycle durations (reduction of schedule) both in the manufacturing and in the construction phases, and creation of flow and value in the production system, which ultimately contribute to an overall reduction in cost

Finally, the authors explored broader research related to other areas of the AEC industry and/or related to other industries to examine potential interactions that can bridge the gap in the integration of RSs and LC in the OC context. The analysis revealed that digital fabrication, CNC, and CAM, have the potential to boost the productivity of manufacturing processes in the manufacturing phase of OC, especially when associated with LC principles such as continuous improvement, and verification and validation. The implementation of UAVs and AGVS along with the LC principles of continuous improvement and verification and validation provides valuable data that greatly benefits the decision-making process for construction managers, field engineers, and superintendents during the construction phase of OC projects. As for the use of wearable devices, one of the main benefits is the improvement of health and safety conditions, mainly in the construction phase, which ultimately contributes to a better flow of production and greater productivity. The results also revealed that some interactions are only possible in the manufacturing phase of OC, emphasizing the importance of OC to foster CA and LC interactions in the AEC industry.

The contributions of this study to the AEC body of knowledge include: (1) proposing a categorization for automation concepts applied to construction, (2) presenting a matrix to identify potential interactions of CA and LC in OC, (3) exploring the interactions of RSs and LC in OC covered in literature and identifying gaps, and (4) proposing potential interactions to fill the research gaps between RSs and LC in the context of OC for further research. The study also aids AEC companies in identifying and understanding potential risks and benefits in the use of new technologies for offsite construction.

Limitations are intrinsic to research and the main limitations of this study includes (1) the sources and keywords used to gather the literature and (2) the thematic analysis used to identify the articles themes may be subjected to the subjectivity of the authors. Finally, future work may include interviews with professionals from industry to validate these findings and expand the study to other interactions of CA and LC not covered in this paper, namely (1) modeling and simulation, (2) digitization and virtualization, (3) sensing, and (4) artificial intelligence and machine learning.

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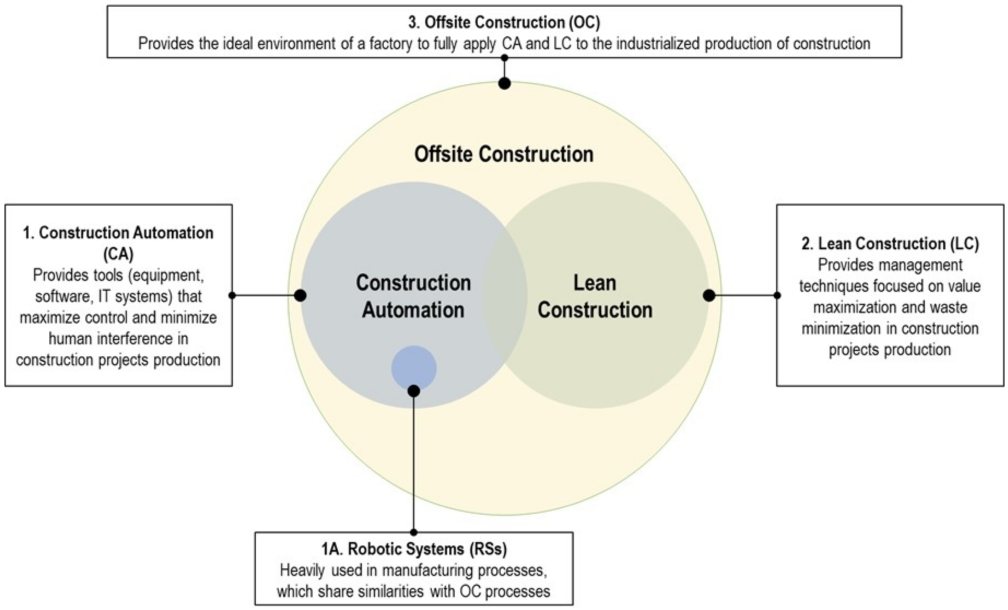


Figure 1. Theoretical Framework

154x93mm (150 x 150 DPI)

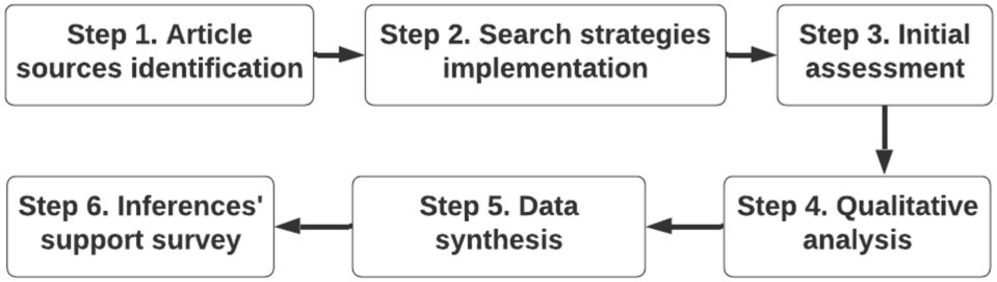


Figure 2. Methodology

152x43mm (160 x 160 DPI)

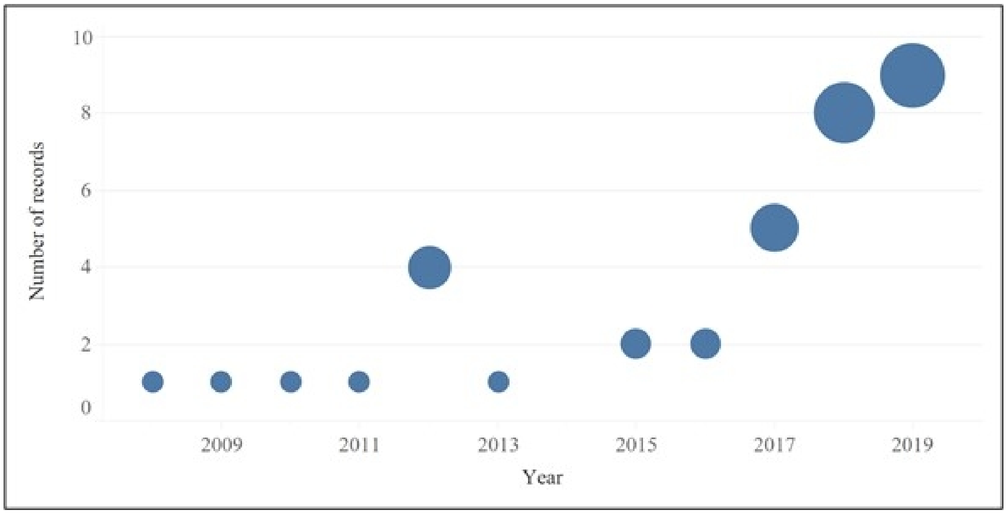


Figure 3. Articles Published by Year (n=35)

156x79mm (96 x 96 DPI)

Table I. Construction Automation Technologies

| Category | Technologies |
| --- | --- |
| Robotic Systems (RSs) | Robots<br>Wearable devices and exoskeletons<br>Unmanned Vehicle Systems: unmanned aerial vehicles (UAVs) and automated guided vehicles (AGVs)<br>Automated equipment<br>Digital fabrication and CNC machines: additive (3D printing), subtractive (machining) manufacturing, and CAM systems |
| Modeling and simulation (MS) | BIM tools: 3D, 4D BIM, 5D BIM, and CAD<br>Augmented reality (AR), virtual reality (VR), and mixed reality (MR)<br>Game simulation<br>Computer models and simulations: simulation-based optimization and agent-based modeling |
| Digitization and Virtualization (DV) | Enterprise information system (EIS): enterprise resource planning (ERP) and electronic document management system (EDMS)<br>Cloud computing and digital platforms<br>Internet of things (IoT)/ internet of services (IoS)<br>Big Data |
| Sensing Systems | Real-time locating systems (RTLS): radio-frequency identification (RFID), infrared (IR), Wi-Fi, ultra-wideband (UWB), and Bluetooth low energy (BLE)<br>Laser scanning, point cloud, and image sensing (still images, time-lapsed images, videos) |
| Artificial Intelligence (AI) and Machine Learning (ML) | Evolutionary techniques: algorithms, genetic algorithms, and evolutionary programming<br>Artificial neural network (ANN), support vector machine (SVM), and rule-based systems (RBS)<br>Data analysis: cluster analysis and data mining<br>Knowledge-based system (KBS): ontology languages and semantic reasoners<br>Natural language processing (NLP) |

Table II. Lean Principles

| Principal Area | Principles |
|---|---|
| Flow process | **Reduction of variability** |
| | Reduction of product variability |
| | Reduction of production variability |
| | **Reduction of cycle times - reduce inventories** |
| | Reduction of production cycle durations |
| | Reduction of inventory |
| | **Reduction of batch sizes** |
| | **Increased flexibility** |
| | Reduction of changeover times |
| | Use of multiskilled teams |
| | **Selection of an appropriate production control approach** |
| | Use of pull systems |
| | Production leveling |
| | **Standardization** |
| | **Continuous improvement** |
| | **Use of visual management** |
| | Visualization of production methods |
| | Visualization of production process |
| | **Design of production system for flow and value** |
| | Simplification |
| | Use of parallel processing |
| | Use of reliable technology |
| | Ensuring the capability of the production system |
| Value generation process | **Ensuring comprehensive requirements capture** |
| | **Focus on concept selection** |
| | **Ensuring requirements flow down** |
| | **Verification and validation** |
| Problem solving | **Going and seeing for yourself - "going to Gemba"** |
| | **Decision by consensus, consideration of all options** |
| Developing partners | **Cultivation of an extended network of partners** |

Adapted from "Interaction of Lean and Building Information Modeling in Construction", by Sacks, R., Koskela, L., Dave, B. A., & Owen, R., 2010, Journal of Construction Engineering and Management, 136(9), p. 973. With permission from ASCE.

Table III. Number of Articles by Journal (n=35)

| Journal | Articles Selected |
|---|---|
| Automation in Construction | 21 |
| Assembly Automation | 3 |
| Journal of Construction Engineering and Management | 3 |
| International Journal of Construction Management | 3 |
| Computer-Aided Civil and Infrastructure Engineering | 1 |
| Construction Innovation | 1 |
| Journal of Civil Engineering and Management | 1 |
| Journal of Cleaner Production | 1 |
| Journal of Management in Engineering | 1 |

Table IV. Matrix of Interactions of Lean Construction Principles and Construction Automation Technologies (n=35)

| Construction Automation Technologies \ Lean Construction Principles | | Reduction of variability | Reduction of cycle times / inventories | Reduction of batch sizes | Increased flexibility | Selection of an appropriate production control approach | Standardization | Continuous improvement | Use of visual management | Design of production system for flow and value | Ensuring comprehensive requirements capture | Focus on concept selection | Ensuring requirements flow down | Verification and validation | Going and seeing for yourself - "going to Gemba" | Decision by consensus, consideration of all options | Cultivation of an extended network of partners |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Robotic Systems | Robots | 20, 22, 23 | 22, 23, 33 | - | 22, 23 | 22 | 22 | - | - | 22, 23, 33 | - | - | - | - | - | - | - |
| | Wearable Devices | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | UAS/ UAV and AGV | 9 | 9 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | Automated equipment | 11, 13, 20 | 6, 11, 13 | - | 6, 20 | 13, 20 | 20 | - | - | 11, 20 | - | - | - | - | - | - | - |
| | DF/CNC, CAM | - | - | - | - | - | 20 | - | - | 20, 21 | - | - | - | - | - | - | - |
| Modeling and Simulation | BIM, 4D BIM, 5D BIM and CAD | 7, 8, 10, 14, 20, 21, 25, 33, 35 | 8, 10, 14, 20, 21, 33, 35 | - | 8, 14, 20, 25, 35 | 12, 19, 20, 24, 33, 35 | 10, 25, 35 | 20, 25, 35 | 10, 12, 13, 17, 18, 19, 25, 33, 35 | 10, 19, 20, 21, 24, 33, 35 | 7, 8, 14, 19, 20, 24 | 8, 20 | 14, 19, 20, 24, 25 | 24 | 24, 35 | 7, 19, 24, 25, 35 | 25 |
| | AR/VR/MR | - | 19 | - | - | - | - | 19 | 17, 19 | - | - | - | - | - | 17, 19 | 19 | - |
| | Game | 18 | | - | - | 18 | 18 | - | 18 | - | - | - | - | - | - | 18 | - |
| | Computer simulations | 1, 4, 11, 13, 21, 26 | 1, 3, 4, 9, 11, 12, 13 | - | 3, 4, 5, 11, 13 | 1, 2, 3, 4, 11 | - | - | 13 | 1, 2, 3, 4, 5, 9, 21 | - | - | - | 7, 11, 16 | - | - | - |
| Digitalization and Virtualization | EIS | - | 30, 35 | - | - | 20, 30, 35 | - | - | - | - | - | - | - | - | - | 17, 20, 30, 35 | - |
| | Cloud computing and digital platforms | 35 | 35 | - | - | 17, 24 | - | - | 17, 35 | 17, 24, 35 | 20, 24 | 20 | 20, 24 | 24 | - | 8, 20, 24 | 20 |
| | IoT/IoS | 31, 35 | 30, 31, 35 | - | - | 17, 30, 31, 35 | - | - | 31, 35 | 30, 31, 35 | - | - | - | - | - | 30, 31, 35 | - |
| | Big Data | 29 | 29 | - | - | 29 | - | - | - | 29 | - | - | 29 | - | 29 | - | - |
| Sensing | RTLS | 29, 31, 34, 35 | 19, 24, 29, 30, 31, 34, 35 | - | 34 | 1, 2, 17, 19, 24, 29, 30, 31, 34, 35 | 17 | 19 | 24, 29, 35 | 1, 2, 24, 29, 30, 31, 34, 35 | 24 | - | 24 | 24, 29, 35 | 24 | 18, 24, 29, 31, 35 | - |
| | Laser scanning, point cloud, image sensing | - | 19 | - | - | 19 | - | 19 | - | - | - | - | - | - | - | - | - |

| Construction Automation Technologies \ Lean Construction Principles | | Reduction of variability | Reduction of cycle times / inventories | Reduction of batch sizes | Increased flexibility | Selection of an appropriate production control approach | Standardization | Continuous improvement | Use of visual management | Design of production system for flow and value | Ensuring comprehensive requirements capture | Focus on concept selection | Ensuring requirements flow down | Verification and validation | Going and seeing for yourself - "going to Gemba" | Decision by consensus, consideration of all options | Cultivation of an extended network of partners |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AI and Machine Learning** | **ES: Algorithms** | 1, 7, 8, 15, 21, 27, 28 | 1, 15, 27, 28, 32 | 15, 16, 28 | 4, 5, 16, 27, 32 | 1, 7, 19 | 28 | - | - | 1, 5, 9, 15, 16, 21, 28, 32 | 7, 8, 27 | 8, 27 | - | - | - | 27 | - |
| | **ANN, SVM, RBS** | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | **Data Analysis** | 6, 31 | 31 | - | 6 | 31 | - | - | 6, 31 | 6 | - | - | - | - | - | 31 | - |
| | **KBS** | 29 | 29 | - | - | 29 | - | - | - | - | - | - | - | - | 29 | - | - |
| | **NLP** | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

Note: Color grading represents number of unique publications (orange = 1 or 2; light orange 3 to 5; yellow = 6 or more)

References: [1] Altaf et al., 2018; [2] Arashpour, Wakefield, Blismas and Maqsood, 2015, [3] Arashpour, Wakefield, Blismas and Minas, 2015; [4] Arashpour et al., 2016 [5] Arashpour et al., 2018; [6] Azzi et al., 2011; [7] Banihashemi et al., 2018; [8] Benros and Duarte, 2009; [9] Chen et al., 2019; [10] Gbadamosi et al., 2019; [11] Goh and Goh, 2019; [12] Han et al., 2012; [13] Innella et al., 2019; [14] Jensen et al., 2012; [15] Ko, 2010; [16] Kong et al., 2017; [17] Li, Xue, et al., 2018; [18] Li, Shen, et al., 2018; [19] Li et al., 2019; [20] Linner and Bock, 2012; [21] Malik et al., 2019; [22] Martinez et al., 2008; [23] Martínez et al., 2013; [24] Niu et al., 2017; [25] Piroozfar et al., 2019; [26] Rausch et al., 2019; [27] Said et al., 2017; [28] Shewchuk and Guo, 2012; [29] Wang et al., 2017; [30] Wang et al., 2018; [31] Xu et al., 2018; [32] Yang et al., 2016; [33] Zhang et al., 2018; [34] Zhao et al., 2019; [35] Zhong et al., 2017.

Table V. Interactions of RSs and LC Principles in OC Supported by the Investigated Literature

| | Interaction description | Evidence from the investigated literature |
|---|---|---|
| A | The use of RSs such as robots, automated equipment, and digital fabrication machines ensures a constant production flow and reduces the variability of OC processes in the manufacturing and onsite construction processes due to its precision, which in turn, reduces defective work and product variability. | Goh and Goh, 2019; Innella et al., 2019; Linner and Bock, 2012; Martinez et al., 2008; Martínez et al., 2013 |
| B | Robots can perform quality inspection of products, reducing product variability, and ensuring higher quality products. | Linner and Bock, 2012 |
| C | AGVs reduce queues in the production line, resulting in less variability in the production flows of OC manufacturing, because it can enhance the storage process of the newly manufactured products. This also contributes to the reduction in the duration of manufacturing cycles. However, the efficient use of AGVs depends on a fully integrated and automated material handling system. | Chen et al., 2019 |
| D | Robotics enabled processes greatly reduce the cycle times, especially in the manufacturing phase, by carrying out the work continuously and reducing the number of manual interventions. | Azzi et al., 2011; Goh and Goh, 2019; Innella et al., 2019; Martinez et al., 2008; Martínez et al., 2013; Zhang et al., 2018 |
| E | Production flexibility increases because robots and automated equipment are fully programmable devices, which adapt to variations in or between production runs, allowing for reduced changeover times and seamless transition between activities. Another aspect is that they can be reconfigured to perform different tasks every cycle. | Azzi et al., 2011; Linner and Bock, 2012; Martinez et al., 2008; Martínez et al., 2013 |
| F | Production control based on a pull system approach is facilitated, as robots and automated equipment only perform a task based on orders, to meet current demand and reduce waste. | Innella et al., 2019; Linner and Bock, 2012; Martinez et al., 2008 |
| G | The relative uniqueness of construction projects and the fragmentation of the AEC industry result in a low level of standardization, which is challenging for higher levels of RSs implementation. The simplification and standardization of building components facilitate the use of robots, automated equipment, and digital fabrication machines, which in turn increase the efficiency of the whole building production process, from design to on-site assembly. Ultimately, simplification and standardization also promote the reduction of production variability. | Linner and Bock, 2012; Martinez et al., 2008 |
| H | The use of automated equipment and digital fabrication machines in construction favor the parallel execution of activities by allowing the interaction of workers and automated equipment. Particularly when OC is adopted, another layer of parallel work is added, as offsite manufacturing processes and onsite construction activities are carried out simultaneously. | Linner and Bock, 2012 |
| I | Focusing on designing the production for flow and value, robots, automated equipment, and digital fabrication machines improve production capacity by increasing productivity when compared with manually performed work. In addition, these technologies are more reliable as they produce better quality products in less time. | Goh and Goh, 2019; Linner and Bock, 2012; Malik et al., 2019; Martínez et al., 2013; Zhang et al., 2018 |

Table VI. Potential Interactions of RSs and LC Principles Within OC to be Further Investigated

| | Interaction explanation | Evidence from literature |
|---|---|---|
| J | Wearable devices and exoskeletons augment workers' physical abilities and reduce physical fatigue and work-related musculoskeletal injuries resulting from performing heavy lifting, repetitive, and prolonged tasks, particularly in the on-site construction phase. Wearable devices equipped with motion trackers and warning indicators reduce accidents (e.g., falls and struck by), which is particularly important in the construction phase. These capabilities of wearable devices contribute to improved labor productivity and safety, helping to keep a more constant production flow, reduce production cycle times and improve product quality while promoting continuous improvement. | Bock et al., 2012; Kim et al., 2019; de Looze et al., 2016 |
| K | UAVs help improve productivity through the intelligent collection and processing of construction site data that can be linked to BIM and other management tools, simplifying information capture and sharing and allowing the monitoring of construction progress. Thus, the adoption of UAVs is in line with several LC principles: (1) reduction of variability, (2) selection of an appropriate production control approach, (3) continuous improvement, (4) use of visual management, (5) design of the production system for flow and value, and (6) product verification and validation. | Anwar et al., 2018; Dupont et al., 2017 |
| L | Digital fabrication machines allow to visualize the production methods and processes and also facilitate prototyping. Prototyping is important to test and inspect products for defects before committing to full tool production, which contributes to reduce product and production variability, and ultimately makes verification and validation of both product and process more efficient in the design and manufacturing phases. | Buswell et al., 2007, 2008; He et al., 2021a; Wu et al., 2016 |
| M | Digital fabrication machines significantly reduce design cycle (potential design time savings of up to 60%) by allowing the interaction of CAD, reverse engineering analysis, rapid prototyping, and rapid tooling and production. The production of components by using CNC machines completely integrated with BIM models is also faster and more flexible than manual production. | Buswell et al., 2008; He et al., 2021b |
| N | The less time it takes and the less uncertainty there is to replenish the stock, the less stock is needed. Therefore, reliable and precise technologies such as robots and automated equipment allow working with reduced inventories in a just-in-time and just-in-sequence basis, especially in the manufacturing phase, since the production capacity will be more constant and reliable. | Bouchard, 2017; Saidi et al., 2016 |
| O | Inventory management with the use of UAVs (e.g., drones) enables more accurate supply-demand reconciliation, ultimately reducing the available inventory. In addition, the use of drones allows constant monitoring of both offsite and onsite material flow. | Anwar et al., 2018; Dupont et al., 2017; Han et al., 2018 |
| P | Considering that robots, automated machines/equipment, and digital fabrication machines can be easily adapted to transitions in production, they are ideal to realize small-batch manufacturing in OC. | Angerer et al., 2015; Buswell et al., 2007; Wadhwa, 2012 |
| Q | Different types of exoskeletons and wearable devices allow the execution of different tasks, improving the flexibility and reducing the variability of production. It is important to have multi-skilled workers trained to use different types of wearable devices. | Bock et al., 2012; Kim et al., 2019 |

| | Interaction explanation | Evidence from literature |
|---|---|---|
| R | Digital fabrication and CNC machines facilitate production leveling and the use of pull system as they are controlled by computers that integrate and precisely control the flow of information, promoting on-demand production, and reducing waste of resources. | Chryssolouris et al., 2009; He et al., 2021b |
| S | Standardized products and processes lead workers to perform tasks more consistently. In this way, it is easier to identify physically demanding activities performed by workers and provide the opportunities to use wearable technology to provide the greatest benefit to workers in terms of performance improvement and injury prevention. | Lo et al., 2020 |
| T | Continuous improvement depends on analyzing the data collected during the construction process, as companies can only improve what they can measure. This process is facilitated and improved with the use of RSs that automatically generate accurate and rich data, necessary to monitor and control the production processes, allowing a comprehensive performance measurement, especially when associated with other CA technologies such as big data, IoT, etc. | Bouchard, 2017; Cho and Kim, 2018; Kontovourkis and Tryfonos, 2020; Saidi et al., 2016 |
| U | R&D is very important in the RS domain, so the more robotic technologies evolve, the more potential benefits they bring to civil construction, resulting in a process of continuous improvement for the AEC industry. | Davila Delgado et al., 2019; Dupont et al., 2017; Saidi et al., 2016; Wu et al., 2016 |
| V | The use of robots and automated equipment in offsite or onsite production allows workers to have time to focus on activities that add more value to the process or to see ways to improve the process by being able to interact and collaborate with robots/machines. | García de Soto et al., 2019; Tsarouchi et al., 2016 |
| W | Robots can work collaboratively with workers, favoring the parallel processing of tasks. Human-robot interaction is a field of high relevance in many industries and is gaining momentum in construction, especially in OC. | García de Soto et al., 2019; Tsarouchi et al., 2016 |
| X | UAV/ ground robot collaboration is based on the use of UAVs to provide accurate data in real time that allows precise commands to be sent to automated equipment on the construction site (e.g., autonomous dozers and excavators). This area of activity still depends on research. | Dupont et al., 2017 |
| Y | Wearable exoskeletons have the potential to improve the performance of construction workers as a reliable technology, which contribute to the lean principle of ensuring the capability of the production system. However, further research and training are needed to confirm the efficient use of this type of equipment in the construction industry. | Kim et al., 2019; de Looze et al., 2016 |
| Z | UAS/ UVA enables remote access to the construction site, allowing problems to be solved as if the stakeholders were at the actual place (Gemba), which eases decision-making. | Anwar et al., 2018; Dupont et al., 2017 |

Table VII. Matrix of Interactions Between RSs and LC Principles

| Lean Construction Principles | Robotic Systems | | | | |
|---|---|---|---|---|---|
| | Robots | Wearable devices | UAVs and AGVs | Automated equipment | DF/ CNC and CAM |
| **Reduction of variability** | | | | | |
| Reduction of product variability | A, B | J | K | A | L |
| Reduction of production variability | A, G | J, Q | C, K | A, G | L |
| **Reduction of cycle times - reduce inventories** | | | | | |
| Reduction of production cycle durations | D | J | C | D | M E |
| Reduction of inventory | N | - | O | N | - |
| **Reduction of batch sizes** | P | - | - | P | P |
| **Increased flexibility** | | | | | |
| Reduction of changeover times | E | - | - | E | M |
| Use of multiskilled teams | - | Q | - | - | - |
| **Selection of an appropriate production control approach** | | | | | |
| Use of pull systems | F | - | K | F | R |
| Production leveling | F | - | K | F | R |
| **Standardization** | G | S | - | G | G |
| **Continuous improvement** | T U, V | J, T, U | K, U | T, U, V | T, U |
| **Use of visual management** | | | | | |
| Visualization of production methods | - | - | K | - | L |
| Visualization of production process | - | - | K | - | L |
| **Design of production system for flow and value** | | | | | |
| Simplification | G | - | K | G | G |
| Use of parallel processing | W | - | X | H | H |
| Use of reliable technology | I | Y | K | I | I |
| Ensuring the capability of the production system | I | Y | K | I | I |
| **Ensuring comprehensive requirements capture** | - | - | - | - | - |
| **Focus on concept selection** | - | - | - | - | - |
| **Ensuring requirements flow down** | - | - | - | - | - |
| **Verification and validation** | - | - | K, O, Z | - | L |
| **Going and seeing for yourself - "going to Gemba"** | - | - | Z | - | - |
| **Decision by consensus, consideration of all options** | - | - | Z | - | - |
| **Cultivation of an extended network of partners** | - | - | - | - | - |