Hamzeh, F., González, V. A., Alarcon, L. F., and Khalife, S. (2021). "Lean Construction 4.0: Exploring the Challenges of Development in the AEC Industry." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 207–216, doi.org/10.24928/2021/0181, online at iglc.net.

LEAN CONSTRUCTION 4.0: EXPLORING THE CHALLENGES OF DEVELOPMENT IN THE AEC INDUSTRY

Farook Hamzeh[1], Vicente A. González[2], Luis F. Alarcon[3], and Salam Khalife[4]

ABSTRACT

In 1994, Lean Construction was understood as the application of Toyota Production principles to Construction. Since then, Lean Construction researchers and advocates have made two fundamental contributions: i) Lean Construction has become a production management theory in its own right; ii) Lean Construction has involved not only production management, but also people, technology, sustainability, safety, education, among others. With the arrival of the "fourth industrial revolution" or Industry 4.0, there has been seminal research attempts to acknowledge the influence of Industry 4.0 on the architecture-engineering-construction (AEC) industry (e.g. Construction 4.0), where the focus has been primarily on technology. However, for Lean Construction to keep evolving and serving the AEC industry, it must embrace the changes propelled by Industry 4.0, but maintain the people-processes-technology triad at its core. We argue that a shift towards Lean Construction 4.0 is needed, paying attention to the synergies between production management theory and digital/smart technologies. The term "Lean Construction 4.0" does represent the vision where we envision the AEC industry to be in the future, rather than its current status. The goal of this paper is not to propose an implementation plan, but to identify research needs and to motivate a discussion on the role of Lean Construction in facing the challenges of adopting Industry 4.0 in the AEC industry.

KEYWORDS

Production management theory, industry 4.0, integration, people-process-technology.

INTRODUCTION

With the rapid advancement in technology and its uses across different domains, industries are facing a new paradigm shift, where advanced digitalization, increased automation, smart future-oriented technologies, and internet of things are at the heart of this shift (Lasi et al. 2014). Industry 4.0, or the fourth industrial revolution, is the term given for this transformation, in which fundamental changes in manufacturing

[1] Associate Professor, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada, hamzeh@ualberta.ca, orcid.org/0000-0002-3986-9534

[2] Associate Professor, Department of Civil and Environmental Engineering, The University of Auckland, Auckland, New Zealand, v.gonzalez@auckland.ac.nz, orcid.org/0000-0003-3408-3863

[3] Professor, Department of Construction Engineering and Management, Pontificia Universidad Católica de Chile, Santiago, Chile, lalarcon@ing.puc.cl, orcid.org/0000-0002-9277-2272

[4] Ph.D. Candidate, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada, khalife@ualberta.ca, orcid.org/0000-0003-1907-4547

productivity, management, economics, and the workforce are expected (Rüßmann et al. 2015). The integration between Lean practices and I4.0 technologies has been already researched in manufacturing (Sanders et al. 2016;) showing the existing synergies, however, the architecture-engineering-construction (AEC) sector is yet to benefit from the existing and emerging technologies that constitute the fourth industrial revolution to deliver projects that are more effective and efficient (Sawhney et al. 2020). Although Lean Construction could be in the driver seat of this transformation, challenges and needed changes are still not clearly laid out.

The consecutive industrial revolutions are a result of leaps in technology starting with mechanization (1st industrial revolution), mass production (2nd industrial revolution), and automation (3rd industrial revolution) (Lasi et al. 2014). Industry 4.0 refers to multiple concepts including: autonomously controlled and digitalized Smart Factory, Cyber-physical Systems (CPS), decentralized self-organization, individualized product and service developments, among others (Lasi et al. 2014). With the transformation from a machine dominant manufacturing to a digital, smart and integrated manufacturing (Oztemel and Gursev 2020), Industry 4.0 is providing companies with higher levels of operational performance, agility, and profitability (Rosin et al. 2020). Rüßmann et al. (2015) indicates the nine technological concepts that represent the pillars for industry 4.0 in manufacturing industries: Big data and analytics, autonomous robots, simulation, systems integration, Internet of Things (IoT), cybersecurity, the cloud, augmented reality, and additive manufacturing.

The AEC industry started following suit by adopting some of these technologies. Research has proven the power of data analytics, such as machine learning and predictive models, in the decision-making process on AEC projects (Mansouri et al. 2020). Virtual reality, augmented reality, and robotics have also been part of the technology trends that emerged into the AEC sector (ex: Ahmed 2018). Moreover, simulation has long been utilized in the AEC industry for purposes such as risk analysis, scheduling, maintenance operations, claims, and process improvements; in fact, simulation is perceived as playing a crucial role in 'futuristic vision of automated project planning and control' (Abdelmegid et al. 2020). As for the Cyber-physical Systems (CPS), some attempts have been made to coordinate virtual models, such as Building Information Modeling (BIM), with the physical construction to improve the control over production processes. Digital twin, a pre-requisite of CPS (Lu et al. 2020), is also an emerging concept that is increasingly embraced in the AEC industry to add social, economic, environmental and business value and optimize projects; however, examples on its implementation are still limited and its broader adoption is still lacking (Building Smart International 2020). Sacks et al. (2020) proposed a digital twin construction concept to production planning and control in conjunction with lean principles, BIM, and artificial intelligence. The digital twin construction is used to proactively analyze and improve design and production through having a data-centric mode of construction management (Sacks et al. 2020). However, the researchers proposing this construct indicated some hurdles for its implementation including: technical barriers (advanced data processing software, AI tools, etc.), organizational fragmentation, and project-specific organizations that are not willing or not ready to make more fundamental changes to processes and systems in AEC projects.

With all the attempts within the AEC industry to leverage the available technologies, it is still deemed behind other sectors. The term Construction 4.0 has been proposed as part of a framework for planning, designing and delivering constructed facilities more efficiently through physical-digital transformations (Sawhney et al. 2020). Innovation is

part of the cyber-physical and digital platforms needed to advance the sector on different levels. Yet, critics still consider the AEC industry is falling short in applying the core principles of Industry 4.0, as a coherent, comprehensive, autonomous, decentralized and fully coordinated system is still missing (Sacks et al. 2020).

On another note, the literature had offered material for connecting lean principles and Industry 4.0 technologies. Mayr et al. (2018) investigated how Industry 4.0 tools and lean management principles relate to each other in the existing literature; their main findings include three viewpoints: (1) lean management is an enabler for Industry 4.0; (2) Industry 4.0 advances lean management; and (3) positive correlation exists between the two. Basically, Industry 4.0 can support the execution of lean goals using for instance real-time value stream mapping (VSM), smart Jidoka system based on CPS, and 3D printing to facilitate one-piece flow and just-in-time delivery (Buer et al. 2018). On the other hand, lean manufacturing is considered a good foundation for Industry 4.0 where lean principles support identifying unnecessary activities and streamlining the process, which in return makes it easier for digitalization and automation (Buer et al. 2018). Accordingly, lean manufacturing and Industry 4.0 are said to have similar goals, complement each other, and their integration is feasible (Mayr et al. 2018). Nonetheless, very little attention has been paid to the connection of lean principles and Industry 4.0 within the AEC context.

When studying the impacts of Industry 4.0 technologies on lean principles, Rosin et al. (2020) indicated that while Industry 4.0 reinforces some lean tools, a major deficiency is the need for supporting people and the team spirit. Lean invests in people as the foundation of the company and it focuses on building teams and develop a "respect for humanity system" (Liker, 2004, chp. 16). Social transformation is foreseeable with the implementation of Industry 4.0 technologies and advancements (such as robots, self-decision-making systems, learning machines, smart cities) (Oztemel and Gursev 2020). In fact, social challenges have been discussed in the literature in connection to Industry 4.0, where risk of cyber-crime, job losses, and other related aspects can arise (Morrar et al. 2017). Therefore, more attention shall be given to the social responsibility and the focus shall go beyond the technological advancement to incorporate human-computer/human-machine interactions, social dynamics, and peoples' needs and experiences.

In general, the AEC industry is witnessing a fundamental growth in regards to technology adoption that is perceived as relatively fast with respect to historical advancements (Mansouri et al. 2020). Accordingly, in the process of embracing Industry 4.0 developments and shifting towards Construction 4.0, a bold move is needed for the Lean Construction community to lay out this integration while discussing the challenges and the opportunities included. Scholars have discussed some of the topics for future research in relation to the synergies between Lean principles and Industry 4.0, where mainly empirical validation is needed to explore further the benefits of this integration (Pagliosa et al. 2019). Despite the benefits of Industry 4.0 technologies, several researchers have expressed their concerns corresponding ethical and moral predicaments that often come with implementing these technologies (Wang and Siau 2019).

For sustaining Lean as a leading strategy of production management in the AEC industry, this paper provides an overview on Lean Construction 4.0 and raises questions and concerns related to the adoption of Industry 4.0. The ultimate goal is to envision the upcoming changes and embrace them all while preserving the people-processes-technology triad at the core of Lean Construction 4.0. Thus, the role of Lean Construction 4.0 is to build a solid basis of responsibility and accountability to do so. The goal of this

paper is to raise awareness about the need for Lean Construction 4.0, and initiate a discussion with Lean thinkers and practitioners with hopes of getting feedback on their concerns or future outlook. This paper focuses on theoretical and practical matters of Lean Construction 4.0 uptake within the AEC industry, but acknowledges that Lean Construction 4.0 is a vision for the future of the AEC industry and inspiration to reach the equivalent of "Industry 4.0" ideal rather than a description of its current status.

WHY LEAN CONSTRUCTION 4.0?

Porter and Heppelmann (2014) claim that smart and digital technologies (SDT) are evolving entire industries, changing industry structure, and altering the nature of competition; they argue that information technology (IT) has transformed twice competition and strategy during the last 50 years; and now, a third IT wave is about to fully take place. In the first IT wave (70's), automation changed how different operations, from order request and billing to CAD and manufacturing resource planning, were carried out, increasing productivity dramatically. In the second IT wave (80's), "Internet" took over which enabled integration levels never seen before across the supply chain (locally and globally). Nowadays, the third IT wave involves smart connected products, where IT is an integral ubiquitous part of this change. This is bringing a promise of unleashing even larger productivity improvements and economic growth. In fact, Porter and Heppelmann (2014)' strategic position about the impact of SDT is coincidental with the underlying benefits from Industry 4.0 in manufacturing (Xu et al. 2018), where SDT triggers more efficiencies, competition, and innovation, enabling a digital transformation of organisations. According to Porter and Heppelmann (2017), there is a gap between the physical world and the digital data generated by SDT due to the inability of current business processes and systems to convey real world information to humans (e.g. representing machinery details in 2D drawings, while in reality they are full 3D entities); thus, it is decreasing decision-making quality. In their view, the human's role is underestimated and they argue that people have unique motor and cognitive skills that technology does not have. Accordingly, powerful human interfaces are required to connect the physical, digital and human worlds effectively. In other words, they acknowledge that the people-processes-technology triad should be at the core of businesses and their strategies.

In contrast, the AEC industry's unwillingness to widely adopt SDT has pushed away the opportunity to achieve the "Industry 3.0 transformation", which is a necessary pre-condition to adopt an "Industry 4.0" state as in manufacturing (Farmer 2016). In fact, there are endemic problems in the AEC industry such as supply chain fragmentation, poor integration of information and production traceability, low levels of innovation, obsolete and myopic production management frameworks (Koskela 2000; Sawhney et al. 2020; Zhou et al. 2016), which are ultimately hindering its competitiveness, efficiency, sustainability and profitability. Even more, these problems have been arguably contributing factors delaying the transition of the AEC industry to the "Industry 3.0" state.

While the "Construction 4.0" concept has opened avenues and opportunities for the integration of STD into AEC project production and business processes (Sawhney et al. 2020), Sacks et al. (2020) stated that this concept has not yet offered a robust, coherent, and actionable framework for implementation that explicitly acknowledges systems' interrelations and autonomy to make both decentralised and fully coordinated decisions in automated supply chains and production. We also argue that Construction 4.0 lacks a deep understanding of the connections between SDT and production management theory.

In that respect, Lean Construction provides production theory principles and a methodological framework for practices to be improved and validated, respectively (Koskela 2000). In fact, Lean Construction has a three-layered framework that explicitly considers “principles and culture”, “practices", and “tools and methods” (Pekuri et al. 2012), which provides the “substratum” to deal effectively with the people-processes-technology triad that an “Industry 4.0” transformation would require in the AEC industry (or to even reach a necessary “Industry 3.0” state). In manufacturing, research revolving around the synergies between Lean Thinking and Industry 4.0 is nascent (Xu et al. 2018), with no clear answers about whether Lean enabling Industry 4.0 implementation is optimum, or the reverse is more effective (Mayr et al. 2018; Xu et al. 2018). However, there is consensus that linking Lean Thinking and Industry 4.0 is feasible and brings positive impacts to those organisations adopting this combined strategy (Mayr et al. 2018; Satoglu et al. 2018; Xu et al. 2018). In that respect, we argue that Lean Construction provides the guiding principles to optimize operations in constructions via SDT. As it turns out, we believe Lean Construction has the potential to enable Industry 4.0 in the AEC industry and maximize the intertwining synergies. In manufacturing, for instance, the term Lean Automation is a blend of Lean Production principles and Industry 4.0 technologies. But automation is not a foreign idea to Lean, as the principles of autonomation acknowledges that repeating and adding value activities are prone to automation (Satoglu et al. 2018), so there is natural extension of the Lean Production principles to Industry 4.0 as such. The point that Satoglu et al. (2018) tried to make is that Lean provides a “waste hunting” and “adding-value” environment on which a truly effective Industry 4.0 implementation can be built upon, where a sense of purpose (production theory) and problem-driven view (Lean-based methodologies) can be provided to the use of SDT. That view can be brought to the AEC industry.

In order to answer the question “Why Lean Construction 4.0?”, we argue that it is necessary to acknowledge that for Lean Construction to be evolved, it cannot ignore the clear connections and synergies with SDT and Industry 4.0 principles. We also acknowledge that over the last three decades, Lean Construction researchers have been investigating the linkages between Lean Construction principles and SDT, sometimes very timidly, unrevealing new avenues of research and development for Lean Construction. Looking at the lean literature, specifically the IGLC conference proceedings from 1996-2016, several studies (88 papers) have focused on BIM, visualization and virtual construction, and on computer application and information systems. However, discussions on advanced technologies advised by industry 4.0 within lean frameworks are still limited. Some researchers started to conceive the importance of providing frameworks and approaches that align process-culture-technology requirements in the digital transformation journey pushed by Industry 4.0 (ex: Romero et al. 2019), yet further intensive studies are still needed under the umbrella of Lean Construction 4.0.

We believe that a Lean Construction 4.0 paradigm, while still aspirational in nature, can provide the “soul” to the people-processes-technology triad when implementing Industry 4.0 in the AEC industry.

VALUE OF LEAN CONSTRUCTION 4.0 FOR BOTH ACADEMIA AND INDUSTRY

In the early 2000s, Peter Drucker, one of the leading voices in management, declared in an interview for "The Economist" (2001): “What has changed manufacturing, and

dramatically increased productivity, are the new concepts. Information, Control, Automation and Robotics Technologies are less important than new ideas about manufacturing, which in advance are comparable to the arrival of mass production 80 years ago". These ideas are known as Lean Management. Peter Drucker also declared: "the essence of management is not techniques and procedures. The essence of management is to make knowledge productive, which is a good starting point for the definition of Lean Management". However, Lean Thinking "means a different approach to business and also implies a different approach to management by people who strive to operate in a Lean manner".

Our experience studying and supporting the implementation of Lean Project Management confirms Drucker's vision, and we believe this is also valid for Lean Construction 4.0. In order to implement Lean Management, the three elements indicated in Figure 1 need to be in a permanent balance: a Management Philosophy inspired by "Lean Thinking"; "Technology" and "Methods" to support the implementation of Lean Management, where Industry 4.0 technologies play a fundamental role; and a transformation of the "Culture" that should host people motivated by Lean transformation. Unfortunately, the need to maintain a permanent presence of these three elements in a Lean implementation is not recognized in many organizations, and this fact likely explains the mediocre or limited results of some implementations and organizational failures. In general, the tendency in organizations is to emphasize technologies, very often ignoring "Philosophy," which is what provides the ideas for "productive knowledge," and the transformation of "Culture," which is essential for people to become the engine of any transformation, is also often neglected.

Philosophy refers to management principles and the concepts of waste and value, which constitute in turn productive knowledge. Culture refers to the required characteristics of people to participate in a Lean transformation. Technology refers to the methods and technologies that support an implementation. The original technologies in the Toyota production system refer to Kanban planning systems, value stream maps, just in time systems, etc. In addition to the original technologies, in projects we currently use Virtual Models (BIM), Last Planner® System, Target Value Design, and we believe this proposed balance is also valid for this new stream of Industry 4.0 technologies.

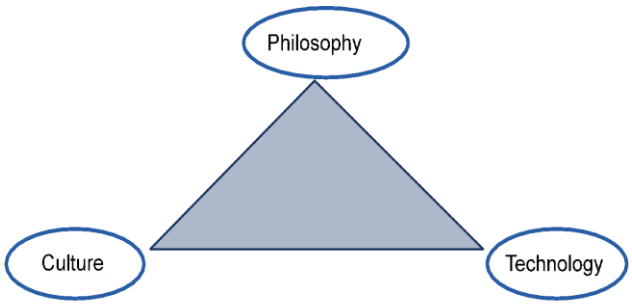

Figure 1: Three Elements of Lean Implementation

Academia can play a relevant role in supporting the AEC Industry in its effort to implement both Lean Construction and Industry 4.0, to make it an integrated effort to implement Lean Construction 4.0. This integration seems to be an appropriate subject of study for academia as shown by studies which explore the integration between Lean practices and I4.0 technologies (Sanders et al. 2016).

Due to the observed difficulties in implementing Lean Management, many studies have suggested the need for utilizing a systematic methodology to implement Lean Management in manufacturing (Mostafa et al. 2013), proposing frameworks that would avoid narrow or short-sighted approaches. Similarly, in construction, there is a need for more systematic implementation approaches where academia can contribute to provide an adequate integrated implementation framework, implementation guides, and appropriate technologies, which could lead to more successful implementation of Lean Construction and Industry 4.0.

There is a huge opportunity for research in a number of fields: obtaining empirical evidence, analyzing synergies, developing conceptual models, frameworks for integrated implementation, etc. These research efforts could probably support government efforts to provide roadmaps for implementation of I4.0 in many countries (Tortorella and Fettermann 2018) and could also benefit from funding coming from these governmental sources. The industry will benefit directly from this stream of research, which has the potential to fully use the existing synergies between Lean Construction and Industry 4.0 including: road maps for digitalization, frameworks for implementation, guidelines for lean construction 4.0 culture, process change, value streams, etc. Researchers will benefit from a better understanding of how Lean Construction and Industry 4.0 can support our effort to create a Lean and Digital construction environment to improve performance in our industry.

A VISION FOR DEVELOPMENT AND IMPLEMENTATION

Over the next 20 years, construction is expected to adopt several Industry 4.0 technologies and incorporate them into the normal way of doing business. One can currently notice several traces of broad attempts to lay down the foundation for future implementations of these technologies. This section envisions such future implementations and highlights the need for Lean Construction 4.0 principles and methods in supporting these implementations.

Starting with *Internet of things (IoT), the Cloud,* and *Big Data & Analytics*, construction projects will include a variety of sensors connected to equipment, tools, material, subassemblies, and even workers. These connected sensors will not only talk to each other but also generate loads of data that will require advanced methods of Big Data management to prepare them to be useful for analysis and for guiding process improvements. Applying the principle of autonomation as part of Lean Construction 4.0 would mean the involvement of white- and blue-collar construction professionals in designing and implementing these technologies to support workers and create a better work environment without confusion or invading workers' privacy and human rights.

Moreover, the use of *Autonomous Robots* and *Additive Manufacturing* such as 3D concrete printing is changing the whole nature of production systems in construction. Advanced robots will feature as future members of construction teams where the dynamics within this new type of team is a paradigm shift in terms of labour resource management and productivity. Lean Construction 4.0 will ensure that work environments are safe, truly collaborative (i.e. human-human, human-machine), inclusive, and transparent.

The construction industry will continue to rely on the use of *Simulation/Digital Twins* (Sacks et al. 2020) to test new changes or develop new improvements on a surrogate system to achieve a greater understanding of the real system. *Artificial Intelligence* and *Machine Learning* will continue to supply construction operations with advanced

algorithms to optimize productivity while reducing cost and time. *Augmented Reality*, *Virtual Reality* and *Holographic Displays* (Hamzeh et al. 2019) will provide system designers, practitioners, and users with a new environment of sensory experiences that will take human-to-system interactions into unprecedented levels of data integration and people's usability. Lean Construction 4.0 will have to ensure that humans remain at the center of these implementations, paying special attention to the users' experience dimension and conditions of satisfaction in the new digitally-driven work environments, without risking any degeneration of work conditions or human relations.

Despite the benefits of Industry 4.0 technologies, several researchers have sounded the alarm on the corresponding ethical and moral predicaments that often come with implementing these technologies. The biggest concerns are centered around the privacy and ownership of data, accessibility, and cybersecurity (Wang and Siau 2019). The future of humanity is also at stake, especially that future technologies might include body and brain implants that will create controversy and several human-right issues. The role of Lean Construction 4.0 is to build a solid basis of responsibility and accountability to preserve and protect the people-processes-technology triad without endangering the human spirit, human life, planet earth, and the ecosystem.

While efficiency is a concern for the construction industry, Lean Construction 4.0 should look behind the direct efficiency of operations and aspire towards systems efficiency. This entails a harmony between 1) human needs, 2) technology, 3) construction processes, and human values of free will, peace, and sustainability. 1) Human needs: are met through engagement and inclusion, team building, training and growth, and understanding that the whole is more than the sum of the parts. The more advanced a system is at reaching a state of harmony, flow, and love between its constituents, the closer it is to achieving the goals of Lean and Systems efficiency. 2) Technology: is put into the context of how it can serve the system, how it can improve work, how it can be used in humane fashion, and how it is connected to the system. Any attempts to jump to system efficiency through a cold control of free will and forceful enforcement through technology will actually lead to degenerating value within the system and aggravating human players including: designers, producers, and users. 3) Construction processes: can be improved by increasing: transparency, value delivered to the customer, and proactive input in a continuously improving lean culture.

DISCUSSION

The goal of this paper is to engage the Lean Construction community in recognizing the need for developing Lean Construction 4.0 to address the challenges of industry 4.0. Accordingly, we present here a list of thought-provoking questions that we ask the readers to ponder upon while also inviting them to engage in the discussion and provide their valuable feedback.

1- Is there a need for Lean Construction 4.0 thinking to provide a production theoretical "substratum" and enable an effective implementation of Industry 4.0 technologies in the AEC industry?

2- What are the necessary adjustments that the Lean Construction community would introduce to Lean Construction 4.0 to cater to future challenges? What is the role of the people-process-technology triad to revamp the Lean Construction research towards a Lean Construction 4.0 ideal?

3- What type of issues would Lean practitioners face when implementing Industry 4.0 technologies? How can Lean Construction 4.0 assist in the digital transformation of firms and business in the AEC industry?

4- What changes will Industry 4.0 bring into the work of professionals in the AEC industry? What is the role of Lean Construction 4.0 in this?

5- What type of training will be required from the future workforce to be "up to date" with Lean Construction 4.0 in terms of processes and technologies?

CONCLUSIONS

This paper has laid out the future needs of the AEC industry for Lean Construction 4.0 principles and established the foundations for development of these principles to match the advancing technologies of Industry 4.0. We have highlighted our concerns and voiced several suggestions of how the future might unfold. We have also posed several questions for discussion and feedback. Answering these questions is an important step towards understanding the need of Lean Construction 4.0 to address the fourth industrial revolution without undermining the triad of people, technology, and processes.

REFERENCES

Abdelmegid, M. A., González, V. A., Poshdar, M., O'Sullivan, M., Walker, C. G., and Ying, F. 2020. "Barriers to adopting simulation modelling in construction industry." *Autom. Constr.*, Elsevier, 111, 103046.

Ahmed, S. 2018. "A review on using opportunities of augmented reality and virtual reality in construction project management." *Organization, Technology & Management in Construction: Int. J.*, 10(1), 1839–1852.

Buer, S.-V., Strandhagen, J. O., and Chan, F. T. S. 2018. "The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda." *Int. J. of Production Research*, Taylor & Francis, 56(8), 2924–2940.

Building Smart International. 2020. *Enabling an Ecosystem of Digital Twins*.

Drucker, P. 2001. "The Economist." *The Economist*, November 3, pg. 12.

Farmer, M. 2016. "The farmer review of the UK construction labour model." *Construction Leadership Council.* United Kingdom.

Hamzeh, F., Abou-Ibrahim, H., Daou, A., Faloughi, M., and Kawwa, N. 2019. "3D visualization techniques in the AEC industry: the possible uses of holography." *ITcon*, 24, 239–255.

Koskela, L. 2000. *An exploration towards a production theory and its application to construction*. VTT Technical Research Centre of Finland.

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., and Hoffmann, M. 2014. "Industry 4.0." *Business & information systems engineering*, Springer, 6(4), 239–242.

Liker, J. K. 2004. *Toyota way: 14 management principles from the world's greatest manufacturer*. McGraw-Hill Education.

Lu, Y., Liu, C., Kevin, I., Wang, K., Huang, H., and Xu, X. 2020. "Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues." *Robotics and Computer-Integrated Manufacturing*, Elsevier, 61, 101837.

Mansouri, S., Castronovo, F., and Akhavian, R. 2020. "Analysis of the synergistic effect of data analytics and technology trends in the AEC/FM industry." *J. Constr. Eng. Manage.*, American Society of Civil Engineers, 146(3), 4019113.

Mayr, A., Weigelt, M., Kühl, A., Grimm, S., Erll, A., Potzel, M., and Franke, J. 2018. "Lean 4.0-A conceptual conjunction of lean management and Industry 4.0." *Procedia Cirp*, Elsevier, 72, 622–628.

Morrar, R., Arman, H., and Mousa, S. 2017. "The fourth industrial revolution (Industry 4.0): A social innovation perspective." *Technology Innovation Management Review*, Talent First Network, 7(11), 12–20.

Mostafa, S., Dumrak, J., and Soltan, H. 2013. "A framework for lean manufacturing implementation." *Production & Manufacturing Research*, Taylor & Francis, 1(1), 44–64.

Oztemel, E., and Gursev, S. 2020. "Literature review of Industry 4.0 and related technologies." *Journal of Intelligent Manufacturing*, 31(1), 127–182.

Pagliosa, M., Tortorella, G., and Ferreira, J. C. E. (2019). "Industry 4.0 and lean manufacturing." *Int. J. Manuf. Technol. Manage.*, Emerald Publishing Limited.

Pekuri, A., Herrala, M., Aapaoja, A., and Haapasalo, H. 2012. "Applying Lean in construction–cornerstones for implementation." *Proc. 20th Ann. Conf. Int. Group for Lean Construction*, San Diego, USA, 18–20.

Porter, M. E., and Heppelmann, J. E. 2014. "How smart, connected products are transforming competition." *Harvard business review*, 92(11), 64–88.

Porter, M. E., and Heppelmann, J. E. 2017. "Why every organization needs an augmented reality strategy." *HBR'S 10 MUST*, 85.

Romero, D., Flores, M., Herrera, M., and Resendez, H. 2019. "Five Management Pillars for Digital Transformation Integrating the Lean Thinking Philosophy." *Proc. 2019 IEEE Int. Conf. on Eng., Techol., and Innovation*, ICE/ITMC 2019, 1-8.

Rosin, F., Forget, P., Lamouri, S., and Pellerin, R. 2020. "Impacts of Industry 4.0 technologies on Lean principles." *Int. J. Prod. Res.*, Taylor & Francis, 58(6), 1644–1661.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., and Harnisch, M. 2015. "Industry 4.0: The future of productivity and growth in manufacturing industries." *Boston Consulting Group*, Boston, MA, USA:, 9(1), 54–89.

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., and Girolami, M. 2020 "Construction with digital twin information systems." *Data-Centric Engineering*, Cambridge University Press, 1.

Sanders, A.,Elangeswaran,C., and Wulfsberg, J.P. 2016. "Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing." *J. Ind. Eng. Manage. (JIEM)*, Barcelona: Omnia Science, 9(3), 811–833.

Satoglu, S., Ustundag, A., Cevikcan, E., and Durmusoglu, M. B. 2018. "Lean production systems for Industry 4.0." *Industry 4.0: Managing the digital transformation*, Springer, 43–59.

Sawhney, A., Riley, M., and Irizarry, J. 2020. *Construction 4.0: An innovation platform for the built environment*. Routledge, Taylor & Francis Group.

Tortorella, G. L., and Fettermann, D. 2018. "Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies." *Int. J. Prod. Res.*, Taylor & Francis, 56(8), 2975–2987.

Wang, W., and Siau, K. 2019. "Industry 4.0: Ethical and Moral Predicaments." *Cutter Business Technology Journal*, 32(6).

Xu, L. Da, Xu, E. L., and Li, L. 2018. "Industry 4.0: state of the art and future trends." *Int. J. Prod. Res.*, Taylor & Francis, 56(8), 2941–2962.

Zhou, Z., Goh, Y. M., and Shen, L. (2016). "Overview and analysis of ontology studies supporting development of the construction industry." *J. Comput. Civ. Eng.*, American Society of Civil Engineers, 30(6), 4016026.