

# Interactions Between Construction 4.0 and Lean Wastes

Mahmoud El Jazzar <sup>a</sup> and Hala Nassereddine <sup>a</sup>

<sup>a</sup>Department of Civil Engineering, University of Kentucky, USA  
E-mail: meljazzar@uky.edu, hala.nassereddine@uky.edu

## Abstract

Lean construction and Construction 4.0 are two prominent concepts challenging traditional practices in the construction industry. The continuous increase in competition and the demand for more efficient project delivery with less waste is pressuring construction companies to adopt these concepts. Body of literature have discussed the benefits of each separately, however, very few have discussed the interaction effect between them. Therefore, using literature, this paper investigates the impact of Construction 4.0 technologies on the eight types of Lean Construction waste. To achieve the research objective, the eight types of waste and the seven Construction 4.0 technologies were first defined. Then, A two-dimensional matrix was generated using 54 research articles to visually represent how each of the seven Construction 4.0 technologies can eliminate certain types of waste. While the impact of Construction 4.0 on waste elimination varies among the technologies, it can be concluded that Construction 4.0 supports Lean waste elimination. Future research should investigate the relationship at different phases of the project including design, and operation. Also, it should investigate additional technologies.

## Keywords –

Lean construction; Construction 4.0; Industry 4.0; Construction Waste; Construction Technologies

## 1 Introduction

The traditional construction management system is characterized by a high level of waste resulting in low productivity, cost overruns, and delays [1]. As a legacy industry, researchers and practitioners started a journey to change the status quo and find a better management system to improve the construction industry. Inspired innovations in manufacturing, Lean Construction emerged as a new paradigm that challenges the traditional approach to construction. According to [2] “Lean is a way to design production systems to minimize waste of materials, time, and effort to generate the maximum possible amount of value”.

The Lean philosophy started to be adopted by the construction sector in the mid-1990s as a new approach

to improve productivity and eliminate activities that do not add value for the customer, thus reducing and eliminating waste[3]. [4] defined waste as the inefficient use of equipment, material, and labor that results in the overutilization of resources needed to construct a facility. [5] offered a generic definition stating that waste is what can be eliminated, including activities, resources, and rules, without reducing customer value.

According to [6], 68% of the time is wasted on non-value adding activities, resulting in poor construction project performance. [1] added that 90% of onsite tasks fall under two types of activities: non-value adding and non-value adding but required activities. [7] showcased that the non-value adding activities consume 9.4% of the project budget, leading to budget overruns. Researchers have well documented that waste, in all of its forms hinders, project workflow, lowers productivity, and increases overall project cost [8]. Therefore, it is crucial that practitioners and researchers identify where improvements are needed in the construction processes in order to minimize the sources of waste, and thus, eliminate waste.

Taichi Ohno, chief engineer at Toyota, identified the following seven types of waste in production in 1988: defects/rework, overproduction, waiting, transportation, inventory, movement/motion, and over processing [9]. A few years later, Womack and Jones added the eighth type of waste, non-utilized workers talent [5]. Researches noted that identifying and defining different types of waste in construction is a strategy to eliminate them [9].

As Lean continued to gain momentum in the construction industry, manufacturing was undergoing another major transformation through the fourth industrial revolution (Industry 4.0). [10] defined Industry 4.0 as “a new technological age for manufacturing that uses cyber-physical systems, Internet of Things, Data and Services to connect production technologies with smart production processes”. The core of this revolution is based on connectivity and interaction between machines and humans through different technologies: Robotics, Augmented Reality, Simulations, The Cloud, Big Data, Internet of Things, Cybersecurity, Additive Manufacturing, horizontal and vertical system integration [11].

Building on the gains of Industry 4.0, construction researchers began to investigate the potential of Industry 4.0 in construction, and as a result, the concept of

“Construction 4.0” emerged to encompass emerging technologies [12].

While various research efforts have discussed how Industry 4.0 technologies can increase and support Lean manufacturing effectiveness by eliminating waste [13], research has not yet explored the connections between Construction 4.0 and Lean construction and how it can be leveraged to eliminate waste. Therefore, this paper investigates how the Construction 4.0 technologies can help eliminate construction waste. To achieve the research objective, a comprehensive literature review was performed using 65 papers that discuss the eight types of wastes in Lean Construction and the different Construction 4.0 technologies. Next, a matrix was developed based on the research corpus to map the interactions between the two variables and showcase how each of the Construction 4.0 technologies assists in reducing wastes at the construction phase.

## 2 Literature Review

### 2.1 Eight Types of Waste

The eight-waste taxonomy was identified by [5][14] for manufacturing, and then later, was adopted by other industries including healthcare, financial, IT, and services [9].

Various studies attempted to expand Ohno’s list of waste. For instance, [15] identified information waste as the loss of talent, capabilities, and behavioral waste. The authors also considered the “failure to speak and listen” as the greatest waste of construction. [16] suggested another type of waste known as “making do” which occurs when a task has started without its predecessors being ready. The author also noted that “making do” is the most critical type of the construction industry.

Given that Ohno’s seven types of waste and Womack and Jones’s eighth waste are the most discussed in the body of knowledge, the matrix presented in this paper is based on Ohno’s taxonomy while taking into consideration the peculiarities of construction.

Construction waste as derived from literature are known as (DOWNTIME):

- **Defects/rework:** it refers to the incorrect work that needs to be repaired, reworked, or replaced. This type of waste covers a major spectrum of construction problems including repair work, work defects, and retesting tasks [17].
- **Overproduction:** it is the process of fabricating material too early, ordering extra material, or delivering activities too early, thus, creating idle periods [17].
- **Waiting:** it occurs when crews wait for long-lead items to arrive, or due to unrealistic schedules, or

when prerequisites are not ready [9][18].

- **Non-Utilized/Unused talent:** it refers to non-utilized employee talent and skills [5].
- **Transportation:** it refers to the unnecessary transportation of people, tools, equipment, or products. It involves unnecessary transportation from the site to the material laydown area [18].
- **Inventory:** it refers to the excess storage of material on-site or at the fabrication yard, work in progress, and unused tools.
- **Movement/Motion:** it refers to unnecessary movement of workers within construction site [19].
- **Extra/Over-processing/Unnecessary work:** it refers to doing things that need not be done, or excessively performed, for example, excessive training time, excessive use of equipment, long approval process which will not add a value to a process [17].

### 2.2 Value and Waste

[20] thoroughly discussed the concept of value and waste in construction and highlighted the importance of identifying customer(s) value before proceeding with any efforts to minimize waste. In addition, the author explained waste elimination cycle and how the efforts to focus on waste elimination alone could lead to the creation of additional waste and not necessarily lead to delivery of customer value. On the other hand, [21] highlighted the challenges in identifying and delivering value since it is dependent on the type of customer(s), which in many cases could lead to conflicts to identify which is more valuable such as choosing between comfort and cost.

### 2.3 Construction 4.0

Inspired by Industry 4.0, the term “Construction 4.0” emerged in the 21st century construction research corpus [12]. Current research highlighted the lack of a consensus on a single formal definition for Construction 4.0 [12][22][23]. However, various authors and organizations attempted to define it. For instance, the European Industry Construction Federation (FIEC) defined Construction 4.0 as the counterpart of Industry 4.0 in the Architecture, Engineering & Construction (AEC) industry and it refers to the digitalization of the construction industry [24][25]. While the definition of Construction 4.0 varies among different researchers and organizations, there is agreement that the adoption of Construction 4.0 will shift the construction process, organizations and project structures from a fragmented to an integrated state [25].

## 2.4 Construction 4.0 Technologies

A review of the literature identified a wide set of Construction 4.0 technologies. This paper focuses on seven of the most frequently discussed Construction 4.0 technologies [23], namely: Integrated Building Information Modeling (iBIM), 3D printing (3DP), Artificial Intelligence (AI), Augmented Reality (AR), Virtual Reality (VR), , Drones, and Robotics.

To understand the impact of Construction 4.0 technologies on different types of construction wastes, it is important to first understand and define the technologies. Therefore, a brief introduction to these technologies is provided.

- **Integrated Building Information Modeling (iBIM)** is considered the higher level of traditional BIM that is integrated and fed by information from different technologies via the cloud [26].
- **3D Printing (EDP)** is the process of creating a complex, physical 3D object from a CAD model. This technology is being used in different industries including healthcare, automobile, as well as the construction industry on mainly small and medium-sized scales [27][28].
- **Artificial Intelligence (AI)** is the simulation of human intelligence processes by machines [29]. Machine learning is considered one of the components of AI where a machine learns from a set of data using statistical methods.
- **Augmented Reality (AR)** is a data publishing platform that allows the user to display information, engage and interact with the published content, and collaborate with others in real-time from remote locations [30].
- **Virtual Reality (VR)** is a computer-generated simulation in which a person can interact with artificial 3D objects with the aid of a 360-degree visions headset [31].
- **Robotics** are machines that can perform or replicate human actions. Currently, they are being used in in the vertical construction sector [32].
- **Drones** are unpiloted small sized aircrafts that are remotely controlled. In recent years, their use in construction has been on the rise for various applications such as surveying and progress monitoring [33].

It is important to note that while each of these technologies has its own attributes, iBIM is considered central to the digitization of the construction industry and in achieving Construction 4.0 integration [34]. Although this paper investigates how each Construction 4.0 can eliminate construction waste, the authors recognize that Construction 4.0 is not about an individual technology, but rather the integration of various technologies. . While

the matrix presented next is two-dimensional, the connectivity between Construction 4.0 needs to be considered to get a full read of the impact of Construction 4.0 and construction waste.

## 3 Methodology

To achieve the research objective, a literature review was performed using Google Scholar to identify papers that showcase the implementation of Construction 4.0 technologies mainly in the construction phase of the construction project. The reviewed documents included articles, company reports, and conference proceedings. Moreover, the search looked for words in the title, abstract, and keywords of the articles, such as “technology”, “iBIM construction”, “Drones Construction”. Furthermore, the results were restricted to English language, limited to 2021-2017 with some exceptions to highly cited papers.

## 4 Construction 4.0 and Construction Wastes Interaction Matrix

The search resulted in a total of 54 research papers related to Construction 4.0 technologies that were reviewed, analyzed, and mapped onto a matrix as shown in Figure 1. The top row represents the eight types of waste and the first column lists the different seven Construction 4.0 technologies. Examples of the interactions presented in the matrix are briefly discussed in the next sections.

### 4.1 Integrated Building Information Modeling (iBIM)

iBIM is considered the core for Construction 4.0 implementation and it plays an essential role in providing a medium of communication between different technologies supported by Internet of Things and Big data [12][22][23][34]. Although the term “BIM” is mentioned in the selected papers, the applications reviewed and discussed in this work refer to iBIM because they showcase the implementation of an advanced form of BIM which communicates with different types of technologies via active cloud links. For instance, [35] showcased an iBIM and RFID workflow use-case which improves material flow processes where the aggregated collected information helped in creating short-term look-ahead plans that assisted in minimizing inventory, improving construction workflow, and minimizing waiting, defects, and material transportation. Having a proper material management and tracking system benefits the overall construction process, and minimizes overproduction and over processing. [36] presented how iBIM can be used to implement a digital

Lean construction management system. As a result of this implementation, the construction team were able to utilize the potential of digital pull planning and the model data, to perform accurate resource planning, and make decisions on site based on the performance data collected via different handheld tools. This study showed how

iBIM plays an important role in minimizing overproduction, over processing, inventory, transportation, movement, and waiting. Additionally, the implemented tool helped enhancing the construction team decision making skills.






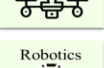

	Defects	Over production	Waiting	Non-utilized/Unused talent	Transportation	Inventory	Movement	Over processing
 iBIM	35,36,54,55,56,57,58,59	35,36,52,53,54,55,56,57,58,60	35,36,52,53,54,55,56,57,58,60	36	35,36,52,53,54,55,56,57,58,60	35,36,52,53,54,55,56,57,58,59,60	35,36,52,53,54,55,56,57,58,59,60	35,36,52,53,55,56,57,58,60
 3D Printing	27,28,38,39,41,61,62,63,64	27,28,38,39,41,61,62,63,64	27,28,38,39,41,61,62,63,64	27,28	27,38,39,41,61,62,63,64	27,28,38,39,41,61,62,63,64	27,38,39,41,61,62,63,64	27,28,38,39,41,61,62,63,64
 AI	43,44,45,66	47	43,44,47,45,65,66		43,44,47,45,65,66	46	43,44,45,46,65,66	45,47,65,66
 AR	48,49,50,51,67,68,69	49,50,67,68	48,49,50,51,67,68,69	48,49,50,51,67,68,69	50,51,49	49	48,49,50,51,67,68,69	48,49,50,51,67,68,69
 VR	50,70,71,72,73	50,70,71,72	50,70,71,73	50,70,71,72,73	50,70		50,70,71,72,73	50,70,71,72,73
 Drones	74,75,76,77,78,79,80,83	74,75,78,80	74,75,76,77,78,79,80	76	74,78,80		74,76,77,78,79,80,83	74,75,77,78,80
 Robotics	81,82,83,84,86,87	82,83	81,82,83,85,86,87		83,87		81,82,83,84,85,86,87	81,82,83,85,87

Figure 1- Construction 4.0 technologies and Waste Interaction matrix

## 4.2 3D Printing (3DP)

Different research papers have showed the positive effects of using 3DP in construction either through simulation or Value Stream Mapping [28][37] or by showcasing real projects physically [27][38][39]. 3DP helps in minimizing unnecessary movement, waiting, transportation, and inventory, by using less material inventory and workers [27][39]. In addition, the technology minimizes traditional concrete defects like honeycombing because it doesn't require the use of frameworks. Moreover, defects that may occur while *printing* can be easily spotted and treated before printing another layer [37][38]. Furthermore, 3DP reduces overproduction and over processing because the speed of printing can be controlled [40][41]. Furthermore, 3DP is help to build more talent among workers because it pushes them to learn new technical digital skills [27][39].

## 4.3 Artificial Intelligence (AI)

AI is considered one of the core technologies for Construction 4.0 [22][23]. The current application derived from literature mainly focused on safety improvement and inspection [42][43][44][45]. When spotting unsafe workers behavior, AI could alert

operation center which allows to prevent injury and as a result prevent defects, and waiting [45]. In addition it can be used for various inspection applications which will help to detect defects and the proper intervention required which will help in minimizing transportation, over processing, and movement [43][44]. Also [46] showcased how AI can be used to minimize inventory and highlight long lead items that needs attention, in addition to detecting any potential future risks, whether environmental, legal, or financial by analyzing the material suppliers' data. Finally, [47] showcased how AI can minimize over production by optimizing project duration and properly levelling the project resources.

## 4.4 Augmented Reality (AR)

[48] showcased how AR can be used with BIM for on-site safety management to help workers visualize danger spots and proactively avoid potential accidents, thus, eliminating possible defects that might occur due to accidents, waiting, and unnecessary movement. The author added that the technology can be used to fetch model data and superimpose it on the real-world environment to inform better decisions that can help in quality inspection and lower approval times, and eventually reduce over processing. [49] demonstrated the use of AR to provide construction personnel all the information needed to perform the work (drawings,

material type and availability) which leads to reduction in overproduction, inventory, and unnecessary transportation of materials and equipment on site. It is worth mentioning that in all the reviewed papers, there was a consensus that AR enhances workers skills, decision making, and safety [48][50][51]

#### 4.5 Virtual Reality (VR)

[50] demonstrated the use of VR to train workers on operating various construction equipment such as cranes and excavators. The training allows workers to safely test different scenarios before performing the work on site, thus, enhancing workers talent and judgment. Understanding the risks and limitations in training also assists in minimizing other types of waste during construction such as unnecessary movement, over processing, transportation, and defects. Similarly, [72] presented how VR can be used to train young wood carpenters. The results of this study suggested that VR training is more efficient than traditional video training and helps trainees to better understand the process and its prerequisites, which results in reductions in defects, waiting, over production, and over processing.

#### 4.6 Drones

[78] presented various applications for drones in construction such as surveying and structural inspection, progress monitoring. The authors also discussed the integration of drones with AR to create real virtual scenes that can enable construction managers and teams to plan material and worker flow on site, in addition to identifying any potential risks, thus, minimizing rework, overproduction, over processing, waiting, movement, and transportation. Furthermore, [74] demonstrated how drones can be utilized to improve construction workflow and safety which will help to minimize over processing, over production, waiting, transportation, movement, and defects.

#### 4.7 Robotics

[83] presented painting robotic applications in construction that aim to improve the construction process and its productivity, reduce site congestion, and lower operation time, all while delivering better quality. The technology is also perceived to reduce safety risks associated with work near edges or at high places. It can be thus concluded from this work that robotics can reduce waste such as defects, overproduction, over processing, waiting, transportation, and movement. Additionally, [87] demonstrated how robotics and AI can be integrated to perform earthworks in a dam project to accurately detect the compaction quality of the rockfill materials in real-time and assess the compaction quality of the entire work

area to provide feedback on the poorly compacted areas in order to help crews to make corrective actions. This application highlights the potential of robotics to minimize defects, overproduction, over processing, waiting, transportation, and movement.

### 5 Discussion and Limitations

Based on the literature and the resulting matrix, it can be concluded that the implementation of Construction 4.0 technologies helps in minimizing the eight types of waste in construction. The analysis also showed that some technologies have more potential to reduce waste than others. For instance, iBIM was shown to minimize all types of waste, while Robotics which does not have interactions with all eight wastes, specifically it doesn't impact inventory non-utilized talent. While the level of interaction between Construction 4.0 and waste varied, in general, different technologies had an impact on at least six types of waste.

The matrix proposed in this paper is theoretical and is based on the 54 reviewed papers and only seven Construction 4.0 technologies. Moreover, as noted earlier, the two-dimensional matrix does not clearly show the connectivity between the various Construction 4.0 technologies. Research limitation can be summed up by the number of papers which represent a sample of the current research related to implementation of Construction 4.0 technologies. Additionally, the waste discussed in this paper are mainly wastes encountered on the jobsite during the construction phase. Other phases of the project life-cycle such as design and operation have not been discussed.

### 6 Conclusions

This research aimed to study the relationship between Construction 4.0 and Lean Construction by investigating the impact of Construction 4.0 technologies on reducing construction waste. Implications of seven Construction 4.0 technologies on eight types of waste were identified through a thorough review of 54 articles. A two-dimensional matrix was generated to visually represent how each of the seven Construction 4.0 technologies can eliminate certain types of waste. While the impact of Construction 4.0 on waste elimination varies among the technologies, it can be concluded that Construction 4.0 supports Lean Construction and waste elimination. Future research can address the limitations of this work by analyzing other Construction 4.0 technologies and their connectivity, considering other phases of the construction lifecycle such as design and facility management, and conducting prototypes or applications that specifically showcase the implications of Construction 4.0 on waste.

## 7 References

- [1] Bajjou ,M.S., Chafi ,A., and En-Nadi ,A. A comparative study between lean construction and the traditional production system. *International Journal Of Engineering Research In Africa*, 29:118–132, 2017.
- [2] Koskela, L., Howell, G., Ballard, G., and Tommelein, I. *The foundations of lean construction*, Routledge,2002.
- [3] Aziz ,R.F. and Hafez ,S.M. Applying lean thinking in construction and performance improvement. *Alexandria Engineering Journal*, 52(4):679–695, 2013.
- [4] Koskela, L. *Application of the new production philosophy to construction*, volume 72Stanford University Stanford,1992.
- [5] Polat ,G. and Ballard ,G. Waste in turkish construction: need for lean construction techniques. :14, 2004.
- [6] Dupin, P. *Le lean appliqué à la construction: comment optimiser la gestion de projet et réduire coûts et délais dans le bâtiment*, Editions Eyrolles,2014.
- [7] Khanh ,H.D. and Kim ,S.Y. Identifying causes for waste factors in high-rise building projects: a survey in vietnam. *KSCE Journal Of Civil Engineering*, 18(4):865–874, 2014.
- [8] Uusitalo, P., Lehtovaara, J., Seppänen, O., and Peltokorpi, A. Waste in design management operations from the viewpoint of project needs. In *Proc 28th Annual Conference of the International Group for Lean Construction (IGLC)*, pages 73–83, Berkeley, California, USA, 2020.
- [9] Koskela, L., Bølviken, T., and Rooke, J. Which are the wastes of construction? In *21st Annual Conference of the Internatiional Group for Lean Construction*, pages 11, Brazil, 2013.
- [10] MacDougall ,W. Industrie 4.0-smart manufacturing for the future. *Berlin: Germany Trade & Invest*, 2014.
- [11] Klinc ,R. and Turk ,Ž. Construction 4.0 – digital transformation of one of the oldest industries. *Economic And Business Review*, 21:393–410, 2019.
- [12] Rastogi, D.S. Construction 4.0: the 4th generation revolution. In *Proceedings of the ILCC 2017 Indian Lean Construction Conference*, pages C288–C298, Madras, India, 2017.
- [13] Yeen Gavin Lai, N., Hoong Wong, K., Halim, D., Lu, J., and Siang Kang, H. Industry 4.0 enhanced lean manufacturing. In *2019 8th International Conference on Industrial Technology and Management (ICITM)*, pages 206–211, Cambridge, United Kingdom, 2019.
- [14] Womack ,J.P. and Jones ,D.T. Lean thinking—banish waste and create wealth in your corporation. *Journal Of The Operational Research Society*, 48(11):1148–1148, 1997.
- [15] Macomber ,H. and Howell ,G. Two great wastes in organizations. *IGLC, Denmark*, :1–9, 2004.
- [16] Koskela ,L. Making-do—the eighth category of waste. 2004.
- [17] Al-Aomar ,R. Analysis of lean construction practices at abu Dhabi construction industry. :17, 2012.
- [18] Denerolle, S. The 8 wastes of lean construction. Online: <https://www.fieldwire.com/blog/eight-wastes-of-lean-construction/>, Accessed: 02/11/2021.
- [19] Bølviken, T., Rooke, J., and Koskela, L. The wastes of production in construction – a tfv based taxonomy. In *Proc. 22nd Ann. Conf. of the Int’l. Group for Lean Construction.*, pages 12, 2014.
- [20] Mossman ,A. Creating value: a sufficient way to eliminate waste in lean design and lean production. *Lean Construction Journal*, 2009:13–23, 2009.
- [21] Bertelsen ,S. Lean construction: where are we and how to proceed. *Lean Construction*, 1:24, 2004.
- [22] Forcael ,E., Ferrari ,I., Opazo-Vega ,A., and Pulido-Arcas ,J.A. Construction 4.0: a literature review. *Sustainability*, 12(22):9755, 2020.
- [23] El Jazzar, M., Urban, H., Schranz, C., and Nassereddine, H. Construction 4.0: a roadmap to shaping the future of construction.Kitakyushu, Japan, 2020.
- [24] Sommer, A. What is construction 4.0 and is the industry ready? Online: <https://blogs.oracle.com/construction-engineering/post/what-is-construction-40-and-is-the-industry-ready>, Accessed: 05/29/2021.
- [25] García de Soto ,B., Agustí-Juan ,I., Joss ,S., and Hunhevicz ,J. Implications of construction 4.0 to the workforce and organizational structures. *International Journal Of Construction Management*, :1–13, 2019.
- [26] AIMashjary ,B.M., Zolkafli ,U.K., and Razak ,A.S.A. Measurement model of iBIM implementation in AECO industry: PLS-PM approach. *Malaysian Construction Research Journal (MCRJ)*, :63, 2020.
- [27] PERI PERI builds the first 3d-printed apartment building in germany. Online: <https://www.peri.com/en/media/press-releases/peri-builds-the-first-3d-printed-apartment-building-in-germany.html>, Accessed: 03/03/2021.
- [28] Rouhana, C., Aoun, M., Faek, F., Jazzar, M.E., and Farook Hamzeh. The reduction of construction duration by implementing contour crafting (3d printing). In *Proceedings of the 22nd Annual Conference of the Int. Group of Lean Construction*, pages 1031–1042, Oslo, Norway, 2014.
- [29] Rao, S. The benefits of ai in construction. Online: <https://constructible.trimble.com/construction-industry/the-benefits-of-ai-in-construction>, Accessed: 06/11/2020.
- [30] Nassereddine, H., Christian, S., Bou Hatoum Makram, and Harald, U. A comprehensive map for integrating augmented reality during the construction phase. In *Proceedings of the Creative Construction e-Conference 2020*, pages 56–64, Online, 2020.

- [31] Kim ,J. Visual analytics for operation-level construction monitoring and documentation: state-of-the-art technologies, research challenges, and future directions. *Frontiers In Built Environment*, 6:575738, 2020.
- [32] Liu, B. Construction robotics technologies 2030. Online: <http://resolver.tudelft.nl/uuid:fcacf6fb-112c-453f-9903-8ec53274153f>, Accessed: 03/03/2021.
- [33] Zaychenko ,I., Smirnova ,A., and Borremans ,A. Digital transformation: the case of the application of drones in construction. *MATEC Web Of Conferences*, 193:05066, 2018.
- [34] FIEC Construction 4.0. Online: <http://www.fiec.eu/en/themes-72/construction-40.aspx>, Accessed: 06/11/2020.
- [35] Chen ,Q., Adey ,B.T., Haas ,C., and Hall ,D.M. Using look-ahead plans to improve material flow processes on construction projects when using bim and rfid technologies. *Construction Innovation*, 20(3):471–508, 2020.
- [36] von Heyl, J. and Demir, S.-T. Digitizing lean construction with building information modeling. pages 843–852, Dublin, Ireland, 2019.
- [37] El Sakka, F. and Hamzeh, F. 3d concrete printing in the service of lean construction. pages 781–788, Heraklion, Greece, 2017.
- [38] Izard ,J.-B., Dubor ,A., Hervé ,P.-E., Cabay ,E., Culla ,D., Rodriguez ,M., and Barrado ,M. Large-scale 3d printing with cable-driven parallel robots. *Construction Robotics*, 1(1–4):69–76, 2017.
- [39] Jewell, N. World’s largest 3d-printed building opens in dubai after 2 weeks of construction. Online: <https://inhabitat.com/worlds-largest-3d-printed-building-opens-in-dubai-after-2-weeks-of-construction/>, Accessed: 03/03/2021.
- [40] Chiabert ,P. and Sini ,F. Lean management in additive manufacturing: a methodological proposal for quality control. :91, 2020.
- [41] El-Sayegh ,S., Romdhane ,L., and Manjikian ,S. A critical review of 3d printing in construction: benefits, challenges, and risks. *Archives Of Civil And Mechanical Engineering*, 20(2):34, 2020.
- [42] Bigham ,G.F. Artificial intelligence for construction safety: mitigation of the risk of fall. :14, 2019.
- [43] Karaaslan ,E., Bagci ,U., and Catbas ,F.N. Artificial intelligence assisted infrastructure assessment using mixed reality systems. *Transportation Research Record: Journal Of The Transportation Research Board*, 2673(12):413–424, 2019.
- [44] lee, S., Kwon, S., Jeong, M., Hasan, S., and Kim, A. Automated on-site quality inspection and reporting technology for off-site construction(osc)-based precast concrete members. Kitakyushu, Japan, 2020.
- [45] Mohan ,M. and Varghese ,S. Artificial intelligence enabled safety for construction sites. 06(06):5, 2019.
- [46] Ferrovial Integrated annual report consolidated management report and financial statements 2020. Online: <https://www.ferrovial.com/wp-content/uploads/2021/02/integrated-annual-report-2020.pdf>, Accessed: 03/03/2021.
- [47] Mohammadpour, A., Karan, E., and Asadi, S. Artificial intelligence techniques to support design and construction. Banff, AB, Canada, 2019.
- [48] Huang ,Z. Application research on bim+ar technology in construction safety management. *Journal Of Physics: Conference Series*, 1648:042019, 2020.
- [49] Lee, K., Kwon, S., Ko, T., and Kim, Y. A study ar based smart device for work management at plant construction sites. Taipei, Taiwan, 2018.
- [50] Ahmed ,S. A review on using opportunities of augmented reality and virtual reality in construction project management. *Organization, Technology And Management In Construction: An International Journal*, 11(1):1839–1852, 2019.
- [51] Chai, C.-S., Lee, C., Lau, S.E.N., Aminudin, E., Loo, S.-C., Gheisari, M., and Abdalrahman, M.A. Integration of augmented reality in building information modeling: applicability and practicality. pages 281–290, Seville, Spain, 2019.
- [52] Bortolini ,R., Formoso ,C.T., and Viana ,D.D. Site logistics planning and control for engineer-to-order prefabricated building systems using bim 4d modeling. *Automation In Construction*, 98:248–264, 2019.
- [53] Crowther ,J. and Ajayi ,S.O. Impacts of 4d bim on construction project performance. *International Journal Of Construction Management*, :1–14, 2019.
- [54] Deng ,Y., Gan ,V.J.L., Das ,M., Cheng ,J.C.P., and Anumba ,C. Integrating 4d bim and gis for construction supply chain management. *Journal Of Construction Engineering And Management*, 145(4):04019016, 2019.
- [55] El Jazzar, M.S. and Hamzeh, F. *Analyzing construction workflow on bim based oil and gas projects*, American University Of Beirut, 2018.
- [56] Gharouni Jafari ,K., Ghazi Sharyatpanahi ,N.S., and Noorzai ,E. BIM-based integrated solution for analysis and management of mismatches during construction. *Journal Of Engineering, Design And Technology*, 19(1):81–102, 2020.
- [57] Heigermoser ,D., García de Soto ,B., Abbott ,E.L.S., and Chua ,D.K.H. BIM-based last planner system tool for improving construction project management. *Automation In Construction*, 104:246–254, 2019.
- [58] Kim ,K., Cho ,Y.K., and Kim ,K. BIM-based decision-making framework for scaffolding planning. *Journal Of Management In Engineering*, 34(6):04018046, 2018.
- [59] Miara ,R.D. and Scheer ,S. Optimization of construction waste management through an integrated bim api. :13, 2019.

- [60] Saffarini ,S.H. and Akbaş ,R. Managing bim-integrated information for effective look-ahead planning. :13, 2017.
- [61] Avrutis, D., Nazari, A., Nematollahi, B., and Sanjayan, J.G. *3D concrete printing technology: construction and building applications*, Elsevier Science & Technology, San Diego, UNITED STATES, 2019.
- [62] Freire, T., Brun, F., Mateus, A., and Gaspar, F. 3D printing technology in the construction industry. pages 157–167, Cham, 2021.
- [63] Hossain ,Md.A., Zhumabekova ,A., Paul ,S.C., and Kim ,J.R. A review of 3d printing in construction and its impact on the labor market. *Sustainability*, 12(20):8492, 2020.
- [64] Kidwell ,J. Best practices and applications of 3d printing in the construction industry. :8, 2017.
- [65] Hua, H. and Zhang, Z. Application of artificial intelligence technology in short-range logistics drones. In *2019 8th International Symposium on Next Generation Electronics (ISNE)*, pages 1–4, 2019.
- [66] Okpala ,I., Nnaji ,C., and Karakhan ,A.A. Utilizing emerging technologies for construction safety risk mitigation. *Practice Periodical On Structural Design And Construction*, 25(2):04020002, 2020.
- [67] Mirshokraei ,M., De Gaetani ,C.I., and Migliaccio ,F. A web-based bim–ar quality management system for structural elements. *Applied Sciences*, 9(19):3984, 2019.
- [68] Ratajczak, J., Marcher, C., Schimanski, C.P., Schweikopfler, A., Riedl, M., and Matt, D.T. BIM-based augmented reality tool for the monitoring of construction performance and progress. pages 467–476, 2019.
- [69] Li ,X., Yi ,W., Chi ,H.-L., Wang ,X., and Chan ,A.P.C. A critical review of virtual and augmented reality (vr/ar) applications in construction safety. *Automation In Construction*, 86:150–162, 2018.
- [70] Muhammad ,A.A., Yitmen ,I., Alizadehsalehi ,S., and Celik ,T. Adoption of virtual reality (vr) for site layout optimization of construction projects. *Teknik Dergi*, 2020.
- [71] Makhkamova, A., Exner, J.-P., Spilski, J., Bender, S., Schmidt, M., Pietschmann, M., Werth, D., and Rugel, D. *Experiences and future of using vr in the construction sector*, 2020.
- [72] Osti ,F., de Amicis ,R., Sanchez ,C.A., Tilt ,A.B., Prather ,E., and Liverani ,A. A vr training system for learning and skills development for construction workers. *Virtual Reality*, 2020.
- [73] Vincke ,S., de Lima Hernandez ,R., Bassier ,M., and Vergauwen ,M. Immersive visualisation of construction site point cloud data, meshes and bim models in a vr environment using a gaming engine. *ISPRS - International Archives Of The Photogrammetry, Remote Sensing And Spatial Information Sciences*, XLII-5/W2:77–83, 2019.
- [74] Alizadehsalehi ,S., Yitmen ,I., Celik ,T., and Arditi ,D. The effectiveness of an integrated bim/uav model in managing safety on construction sites. *International Journal Of Occupational Safety And Ergonomics*, 26(4):829–844, 2020.
- [75] Anwar ,N., Izhar ,M.A., and Najam ,F.A. Construction monitoring and reporting using drones and unmanned aerial vehicles (uavs). :9, 2018.
- [76] Gheisari ,M. and Esmaeili ,B. Unmanned aerial systems (uas) for construction safety applications. *Construction Research Congress*, :9, 2016.
- [77] Hamledari, H., Davari, S., Sajedi, S.O., Zangeneh, P., McCabe, B., and Fischer, M. UAV mission planning using swarm intelligence and 4d bims in support of vision-based construction progress monitoring and as-built modeling. In *Construction Research Congress 2018*, pages 43–53, New Orleans, Louisiana, 2018.
- [78] Li ,Y. and Liu ,C. Applications of multirotor drone technologies in construction management. *International Journal Of Construction Management*, 19(5):401–412, 2019.
- [79] Umar ,T. Applications of drones for safety inspection in the gulf cooperation council construction. *Engineering, Construction And Architectural Management*, ahead-of-print(ahead-of-print) 2020.
- [80] Vasquez, V. Five case studies for drones in construction. Online: <https://www.constructionexec.com/article/five-case-studies-for-drones-in-construction>, Accessed: 03/02/2021.
- [81] Delgado ,J.M.D. Robotics and automated systems in construction\_ understanding industry-specific challenges for adoption. *Journal Of Building Engineering*, :11, 2019.
- [82] Kang, J.H., Subramanian, A.G., Lee, J., and Faghihi, S.V. *Robotic total station and bim for quality control*, CRC Press, 2012.
- [83] Jayaraj ,A. and Divakar ,H.N. Robotics in construction industry. *IOP Conference Series: Materials Science And Engineering*, 376:012114, 2018.
- [84] Muthugala ,M., Vega-Heredia ,M., Mohan ,R.E., and Vishaal ,S.R. Design and control of a wall cleaning robot with adhesion-awareness. *Symmetry*, 12(1):122, 2020.
- [85] Tankova ,T. and da Silva ,L.S. Robotics and additive manufacturing in the construction industry. *Current Robotics Reports*, 1(1):13–18, 2020.
- [86] Wang ,Z., Li ,H., and Zhang ,X. Construction waste recycling robot for nails and screws: computer vision technology and neural network approach. *Automation In Construction*, 97:220–228, 2019.
- [87] Zhang ,Q., An ,Z., Liu ,T., Zhang ,Z., Huangfu ,Z., Li ,Q., Yang ,Q., and Liu ,J. Intelligent rolling compaction system for earth-rock dams. *Automation In Construction*, 116:103246, 2020.