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Review

Lean Practices Using Building Information Modeling (BIM) and Digital Twinning for Sustainable Construction

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Abstract: There is a need to apply lean approaches in construction projects. Both BIM and IoT are increasingly being used in the construction industry. However, using BIM in conjunction with IoT for sustainability purposes has not received enough attention in construction. In particular, the capability created from the combination of both technologies has not been exploited. There is a growing consensus that the future of construction operation tends to be smart and intelligent, which would be possible by a combination of both information systems and sensors. This investigation aims to find out the recent efforts of utilizing BIM for lean purposes in the last decade by critically reviewing the published literature and identifying dominant clusters of research topics. More specifically, the investigation is further developed by identifying the gaps in the literature to utilize IoT in conjunction with BIM in construction projects to facilitate applying lean techniques in a more efficient way in construction projects. A systematic review method was designed to identify scholarly papers covering both concepts "lean" and "BIM" in construction and possibilities of using IoT. A total of 48 scholarly articles selected from 26 construction journals were carefully reviewed thorough perusal. The key findings were discussed with industry practitioners. The transcriptions were analyzed employing two coding and cluster analysis techniques. The results of the cluster analysis show two main directions, including the recent practice of lean and BIM interactions and issues of lean and BIM adoption. Findings revealed a large synergy between lean and BIM in control interactions and reduction in variations, and surprisingly there are many uncovered areas in this field. The results also show that the capability of IoT is also largely not considered in recent developments. The number of papers covering both lean and BIM is very limited, and there is a large clear gap in understanding synergetic interactions of lean concepts applying in BIM and IoT in specific fields of construction such as sustainable infrastructure projects.

Keywords: digital construction; lean; lean construction; Building Information Modeling (BIM); Internet of Things (IoT); Digital Twin; computer-aided engineering (CAD)

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1. Introduction

Lean construction [1] and advanced digital technologies including Building Information Modeling (BIM) [1] and Internet of Things (IoT) are increasingly utilized in building and infrastructure construction [2–6], but mainly ignored to utilize the combination of both BIM and IoT for improving the efficiency in construction. In fact, the concept of industry 4.0 in construction [7], including relevant technologies to Cyber-Physical Construction Systems (CPCS) [8,9] can be exploited for lean construction. The integration of BIM emerging technologies such as Digital Twin and Cyber-Physical systems [10,11] can be incorporated into IoT platforms to improve the information exchange and provide real-time data. Lean has positive effects on operational businesses such as manufacturers and construction. However, there is an opportunity to utilize new digital technologies [12–15] to help to perform this concept in an appropriate way in construction sites. Improvements in performance may occur using digital systems to turn guidelines to the system in a common language available to all project stakeholders. In addition, sensors are required to measure performance in a real-time manner. BIM and IoT are powerful technology with many unexplored applications, which potentially can improve lean implementation. BIM is known as one of the core proven technologies in the construction industry; scholars intend to link other innovations and tools to BIM to exploit BIM capability for different purposes such as safety [16], life cycle cost optimization [17], quality control, and a common communication channels among stakeholders. BIM is a collection of innovative technology, processes, and policies that affect the industry deliverables, relationships, and roles [18]. BIM enables project quality enhancement, accurate timetables scheduling, and total project costs reduction [19]. BIM has been used for generating and managing parametric models of buildings for document errors and rework reduction, consequently the time of the design process decreases [20], which enables digital model creation, construction design, the operation management of the construction process, and project life management achievement [21]. As the interactive relation and integrative application of lean and BIM are expected to be effective [22], the aim of this review is to critically identify the gaps and incoherence in relevant literature to conceptualize the lean and BIM integration and to develop the new research directions in this discipline.

From the sustainability perspective, a large number of papers examined the BIM capability in estimating the embodied environmental impact of buildings, performing life cycle assessment during design and energy assessments of buildings [23–27]. Some others used BIM to reduce variability, reduce cycle times, reduce batch sizes, increase flexibility, and standardize designs [24]. However, the interaction of BIM and lean techniques to exploit the BIM capability in a systematic way is mostly ignored. For example, Akinade et al. [28] and Liu, et al. [29] discussed that minimizing design waste and construction waste minimization (CWM) has received very little attention. In fact, BIM is not developing based on lean principles to control resources in an automated manner and systematically analyze wastes in each activity during construction. The main reason is that controlling resource use and waste during construction requires a systematic method to update BIM during construction, which should be already being designed based on lean principles; otherwise, it cannot fully address lean concepts. The concept of lean was developed by Toyota and rapidly evolved in recent years [29].

Since World War II, Toyota developed a novel system of management, which concentrated on the waste decrease in all its operational aspects to compete with its rivals specially. Therefore, lean, which causes inventories and lead-times reduction and quality and productivity improvement, were known as Toyota Production System [30,31]. Lean manufacturing not only enables the reduction of the waste but also increases the value via minimizing the waste. The objectives of lean production include (a) value identification and transference to the customers, (b) manufacture organizing as an ongoing flow, (c) making the production perfect and trustworthy flow through data distribution and making the decision, and (d) perfection tracking on customer order delivery according to his/her requirements with no inventory [32–34]. Waste types addressed in lean are transport, material wastes, time, movement, processing, inventory, and producing inventory production [35]. Numerous industries throughout the world have known and practiced lean production as the most effective novel paradigm in production [36]. In 1992, the lean manufacturing approach diffusion in construction was reported by Koskela [37], who introduced the paradigm of manufacture management that conceptualizes the manufacture in three supplementary methods, containing transformation, flow, and value generation (TFV) theory of production. TFV theory of production has been later formulated and led to the lean construction discipline generation that has transformed the current management of construction [37]. However, construction literature has paid little attention to develop guidelines and advanced information systems to utilize lean principles. Rather, the literature separately followed-up the agenda for developing the lean conceptual models, further not realizing the capability of emerging digital systems including BIM and IoT. The aim of this paper is to review the practice of utilizing Digital Twin, IoT, and cyber-physical systems in corporations with BIM for applying lean principles in the construction industry during the last decade. The first objective is to present the bibliographic information of the relevant literature in the last decade. The second objective is to identify the main conceptual themes and research directions in the literature, and consequently to identify gaps and directions for future studies.

2. Method and Procedures

Step 1: Databases Selection for Identifying Lean BIM Articles

This step was conducted in two stages. At first, to acquire relevant journals to lean and BIM in the construction industry, related publications were chosen from Scopus (https://www.scopus.com/sources). As the scope of this research was mainly in the construction industry, at this stage, journals were chosen using keywords such as "building," "architecture," "construction," "engineering," "BIM," "lean construction," "project management," "civil," and "building technology" to cover all aspects in this discipline. According to the Cite-Score metric in the Scopus database, which is launched by Elsevier, 16 international peer-reviewed journals whose Cite-Score metric is more than 1.5 were identified. The first search strings and the preliminary search resulted in 961 articles using the following string: (TITLE-ABS-KEY (IOT OR "Internet of Things" OR "cyber-physical systems") AND TITLE-ABS-KEY (BIM OR "building information model*" OR "Digital Twin")). The second search strings and the preliminary search resulted in 619 articles were found in Scopus using following the string: (TITLE-ABS-KEY (lean), AND TITLE-ABS-KEY (IOT OR "Internet of Things" OR "cyber-physical systems" OR BIM OR "building information model*" OR "Digital Twin")) and 14 articles were found in Scopus using the string: (TITLE-ABS-KEY (lean) AND TITLE-ABS-KEY (IOT OR "Internet of Things" OR "cyber-physical systems") AND TITLE-ABS-KEY (BIM OR "building information model*" OR "Digital Twin") AND TITLE-ABS-KEY (construction industry OR "building" OR "architecture*")).

Step 2: Primary Search

The keyword "lean" was the primary controlled criteria and a keyword for selecting papers. The database was used to conduct the search and identify papers published between the years 2000 and 2020, utilizing the criteria in a specific area, including titles, keywords, and abstracts.

Step 3: Lean and BIM Articles Refinement

Several types of research were conducted [33] regarding different fields of lean such as performance improvement of lean [38], teaching lean [33], and transfer of lean techniques [39]. In this step, we filtered articles solely about "BIM" and "lean" in titles, keywords, or abstracts. Consequently, after this step, the number of papers was decreased to 52.

Step 4: Concentrate on Lean and BIM in Construction Industry Articles

In this step, we further filtered the 52 lean and BIM articles only in the construction and civil engineering discipline and excluded articles in the automotive industry, pharmaceutical industry, insurance industry, and service industry. After this step, the number of relevant articles was reduced to 48 and the number of journals was reduced to 41, as listed in Table 1, while Figure 1 presents the method used for collecting, selecting, and filtering relevant articles.

Table 1. Reviewed articles related to Building Information Modeling (BIM) and Lean in construction.

Journal	Cite Score	Lean and BIM in Construction
Automation in Construction	9.5	8
Lean Construction Journal	2.6	5
Electrical Construction and Maintenance	0	4
Journal of Construction Engineering and Management	5.8	4
Construction Innovation	3.8	3
Engineering Construction and Architectural Management	2.5	3
Sustainability Switzerland	3.2	2
Benchmarking	3.6	1
Advanced Science Letters	-	1
Ain Shams Engineering Journal	4.6	1
Applied Sciences Switzerland	2.4	1
Computer-Aided Civil and Infrastructure Engineering	12	1
Construction Management and Economics	4.4	1
International Journal of Civil Engineering and Technology	–	1
International Journal of Sustainable Built Environment	–	1
Open Construction and Building Technology Journal	1.8	1
Practice Periodical on Structural Design and Construction	1.1	1
Revista De La Construccion	0.8	1
Science and Technology for the Built Environment	2.6	1
Structural Survey	–	1
Sustainable Cities and Society	7.5	1
Journal of Engineering, Design, and Technology	1.5	1
Journal of Object Technology	1.7	1
ENR (Engineering News-Record)	0.00	1
Military Engineer	0.00	1
Modern Steel Construction	–	1

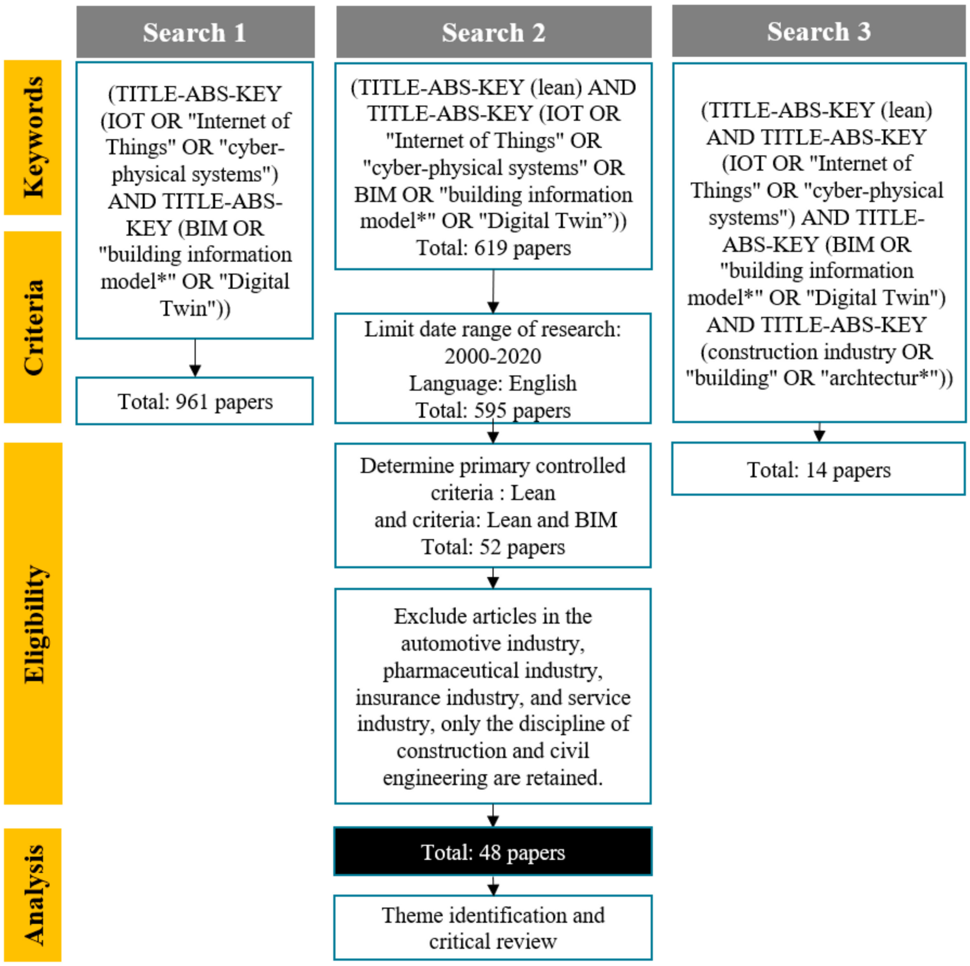

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Figure 1. Flowchart for identifying relevant papers in Scopus.

Step 5: Network and Content Analyses of Selected Articles

The thematic analysis technique was used for synthesizing and comparing the qualitative data. This method is known as an effective way of identifying important recurring themes and useful for structuring the data within each theme [31,40,41]. Figure 2 illustrates the systematic literature review (SLR) steps, objectives, and methods in this research. Network analysis will be carried out in order to identify the bibliometric network of coauthorship and the relationship of co-occurrence of keywords within the data set [40,42]. The objectives of this section are to identify the relationship between key authors in the field, to explore the keywords shifts in the recent three years, and to identify the main clusters of articles in the literature.

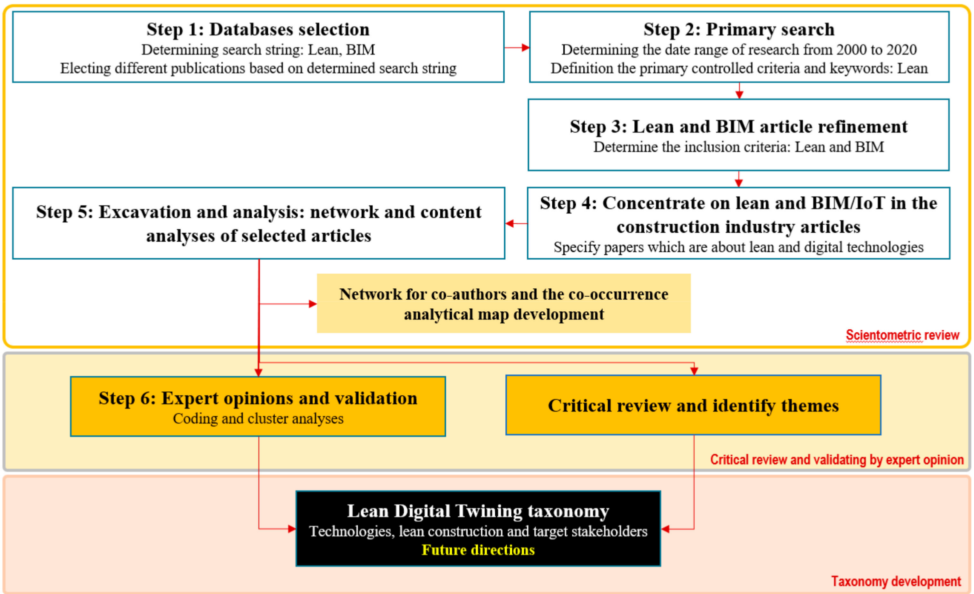


Figure 2. SLR steps, objectives, and methods for identifying lean-Building Information Modeling (BIM) development and directions.

Step 6: Expert Opinions and Validation

In the last step of the investigation, we obtain the opinions of four practitioners from the construction industry to find out whether the results of the review can be verified. The questions asked to the practitioners are as follows: What do you think about the relationship between lean concepts and BIM in construction projects? Can lean be an important motivator for BIM utilization in construction projects? What are the BIM adoption and implementation challenges for lean BIM practice include?

The respondent's transcripts are analyzed using coding (i.e., node creation) and thematic analysis. The main objective of this section is to verify the findings of the SLR and compare the literature findings with the practical issues.

3. Analysis of Research Trends

The title, keywords, cited number, authors, and journals of the 48 selected articles are listed in Table 2. Besides, a specific number is attributed to each paper; so, in the following parts of the paper, the specific number of each paper was used as codes instead of their titles.

Table 2. Summary of selected articles related to lean and BIM.

Paper ID	Title	Cites	Keywords
21	Interaction of lean and BIM [23]	277	Computer-aided design (CAD); Information technology (IT); Lean
7	BIM technology adoption for lean architectural practice [43]	261	BIM; Technology adoption; Design; Lean efficiency
8	Requirements of BIM—lean production management [44]	181	BIM; KanBIM; Lean; Visualization; Production control
34	BIM adoption in architecture [45]	130	Knowledge management; Action research; Modelling; Small to medium-sized enterprises (SME)
22	A workflow to support lean construction [46]	121	CAD; Imaging process; Interfaces; Lean; Safety
2	Enhanced lean construction using the Internet of Things (IoT) standards [47]	86	BIM; IoT; Interoperability; Lean construction; Supply Chain
3	Resource location tracking using BIM for safety	76	BIM; safety; Global positioning system (GPS); Lean; Resource location tracking
5	Using social network theory to evaluate BIM-lean practice [48]	51	Design errors; Social network theory; Simulation; BIM; Lean
4	Productivity improvement of precast shop drawings generation using BIM [49]	48	BIM-based workflow; Lean; Parametric BIM; Precast shop drawing generation; Process re-engineering
20	Enabling BIM adoption for lean purposes: Indian cases [50]	35	BIM adoption; Coordination; Ethnographic action research; IT; Last planner system (LPS); Lean

4. Analysis of Document Type and Source Type

The search was limited to identify articles, excluding review papers, conference papers, and books. The 48 chosen articles include 41 (85%) journal articles and 7 (15%) trade publications. Only the 41 journal articles were used for this review. Figures 3 and 4 show the network created based on the database and show some scholars of the selected database who are involved in this field and the main keywords used in the selected database.

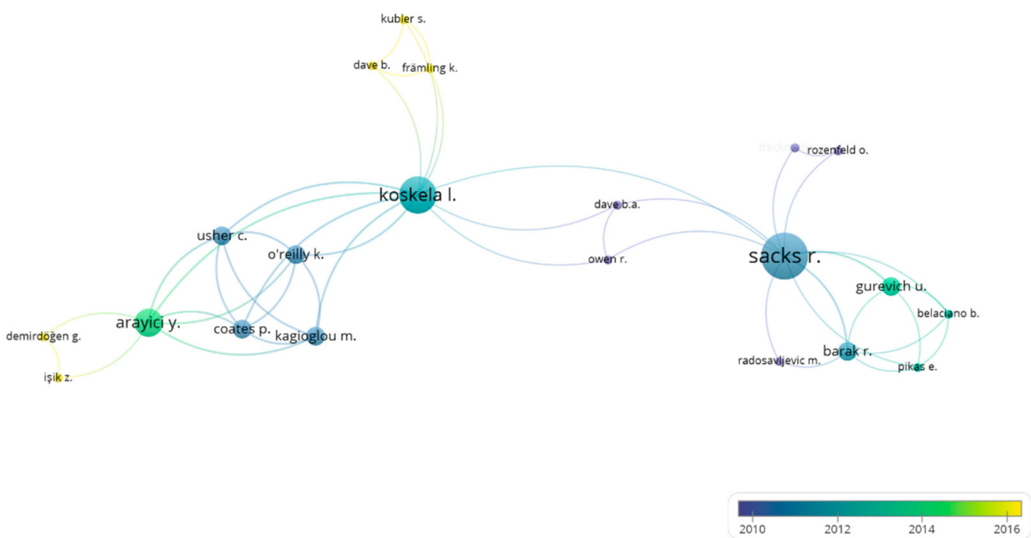


Figure 3. Network for coauthors (out of 115) of 48 articles published in the selected database using full counting.

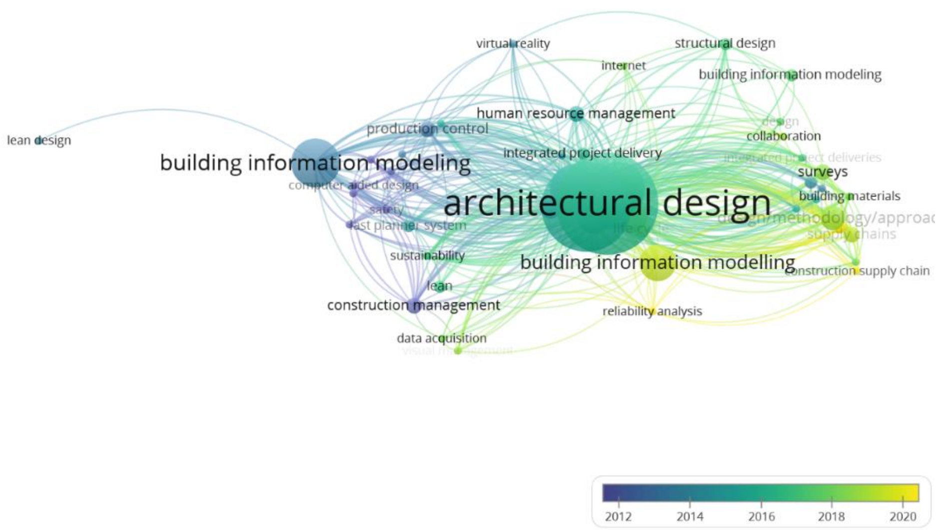


Figure 4. Co-occurrence analytical map of keywords created on 48 articles. With the minimum number of co-occurrence of two, a total of 61 keywords out of the sample of 432 keywords are shown. Note: different colors show a different cluster of keywords.

4.1. Time Span

Figure 5 illustrates the number of published papers by the keywords "lean," and the selected technologies (described in the keywords column in Table 2) from 2010 to 2020. By the keywords "lean and BIM," a few articles were published before 2009. In 2010 and 2011, the number of papers grew to 4 and 6, respectively. The number of papers decreased to 4 in 2012, 2013, and 2014. In 2015, the number of published articles increased to 7, and since 2015, an increasing trend was visible. In general, the increasing trend of article number by all three keywords indicates an enhancement in the importance of these issues in civil engineering research. However, despite a large number of papers about lean or BIM, the number of articles on both lean and BIM is significantly lower.

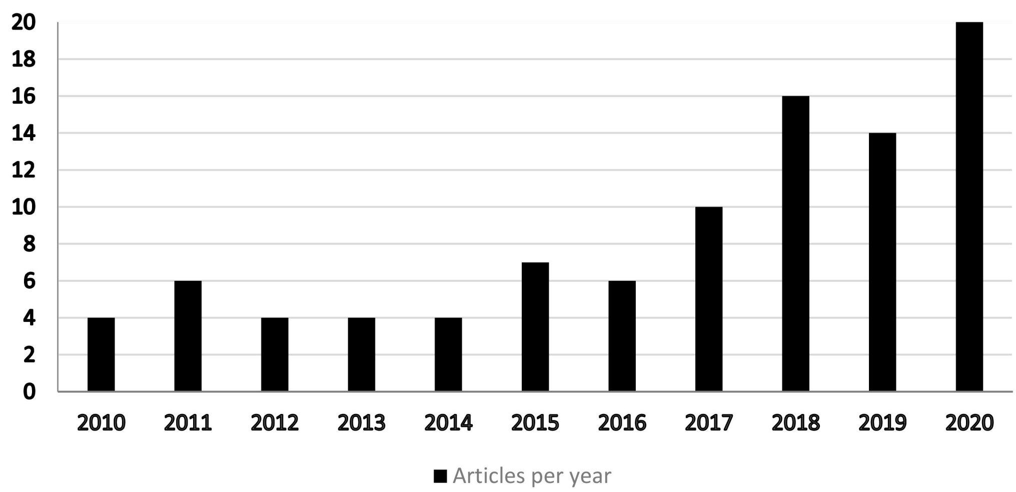


Figure 5. Articles published per year from 2000 to 2020 (December) focusing on digital tools and lean.

4.2. Journal Article Distribution

Figure 6 illustrates the distribution of the 48 articles in various journals. The journal of "Automation in Construction" has the highest share by publishing eight articles (equal to 17%), followed by "Lean Construction Journal" (10%), "Electrical Construction and Maintenance" (8%), and "Journal of Construction Engineering and Management" (8%).

Figure 6 shows that more than 40% of the 48 publications were published in these four journals. It demonstrates that despite the importance of lean and BIM in construction, most of the related research was published in just four journals.

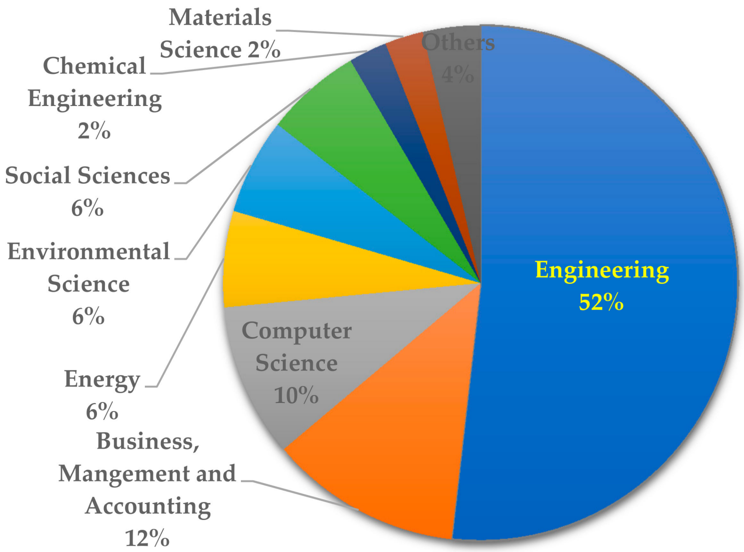


Figure 6. Distributions of papers in different fields from 2000 to 2020 (December). Note: Others consists of arts and humanities, mathematics, physics, and astronomy.

5. Case Study on Most Cited Four Articles Regarding Lean and BIM

5.1. Case Code 21

Case code 21 [23] aims to identify the interaction of lean construction and BIM and accurate analysis of the numerous characteristic interactions between lean and BIM. The authors of the article concluded that despite the significant differences between lean and BIM, both have a great impact on civil engineering practices. A framework was presented by the authors, and as a result, they recognize 56 negative and positive interplays. It was depicted that there is a great deal of synergy between lean and BIM, and their combined application has a far greater improving impact than a separate application on construction processes. Lean principles and BIM implementations should be considered together as an integrated procedure.

The scope of this article covers the entire construction project process and life cycle. The method applied in this article belongs to constructive/design science research since it suggested a conceptual framework for analyzing the interaction of lean and BIM as transformative technologies.

The article recommended that (a) companies and projects should adopt BIM beside lean principles to increase the outcomes of lean; (b) desired benefits must be defined to achieve more affirmative interplays between lean and BIM-based on the manageable experience; and (c) the theory of production in construction must be considered regarding material and information processes changes, tools of BIM, and the principles of lean construction to realize possible benefits of lean and BIM integration.

The significances of the study [23] are twofold. First, the proposed framework could be useful for future empirical research. Second, this framework, along with the analysis, could be perceived as an exemplar of the interactions between IT and the systems of production that they serve.

5.2. Case Code 7

Case code 7 [43] aims to provide a comprehensive and systemic assessment and evaluation of the relevant BIM technologies as part of the adoption and implementation of BIM in lean practices. In this article, the challenges of BIM adoption and implementation for lean practices are implied, including (a) removing the change persistence, (b) encouraging individual for realizing the BIM potential value than 2D drafting, (c) adapting available workflows to lean related processes, (d) teaching BIM to individuals, (e) the necessary assist and integration of team members, and (f) recognizing different stakeholders' accountabilities in new procedures. It concludes that a bottom-up approach and top management support are needed for individual engagement in adopting BIM, to ensure the improvement of individuals' skills and the increase of companies' competency, to use the prosperous strategies regarding change management, and to reduce any possible persistence against change.

The scope of the article was limited to architectural and construction companies. The method was a case study through action research philosophy [51] as a bottom-up approach conducted as a knowledge transfer partnership (KTP) research between the University of Salford and John McCall Architects (JMA), a small and medium-sized enterprise (SME) in Liverpool. Developing lean design practice through the adoption of BIM is the main aim of the KTP. The approach of the implementation of BIM uses a sociotechnical vision, which considers the technology implementation of the sociocultural environment that prepares its implementation context. The method of this investigation is action research-oriented qualitative and quantitative approaches for detection, comparison, and test. In fact, this method provides "learning by doing." Action research includes three phases [51]. The first phase focused on the identification of the most appropriate BIM tool for lean construction based on the context and specific aspect of the company. The second phase focused on the lean design process attained by enhanced BIM comprehension and knowledge. A deeper understanding of BIM and the needs for further improvement were gained in the third phase.

The article recommended that new applications such as facility management could be adopted to maintain the ongoing improvement of lean and BIM adoption in the industry. The significance is that it represents a systematic approach for BIM adoption in architectural practices.

5.3. Case Code 8

Case code 8 [44,52] provides a strong platform to visualize workflow in control systems that enable pull flow and deeper cooperation between teams on- and off-site. The KanBIM research goal is offering, developing, and testing a BIM-enabled system for production planning support, and daily control of production on construction sites.

The requirements for the performance of a BIM-enabled pull flow construction management system based on the Last Planner System (LPS) known as "KanBIM" were determined. The paper concludes that KanBIM system has a key role in individual decision support, coordination of team members and weekly negotiation about work plans, schematization granularity decrease to a diurnal level, real-time function restrictions assessment for calculating maturity of the task, and the language/action prospect implementation.

The scope of the article is limited to the construction process, and the research method involved four steps, namely, (a) requirements definition; (b) analysis of process and design system; (c) coding of functional mock-ups of its interfaces; and (d) assessment of the system in focus three group workshops. The significance of the article is that the system developed has the potential for workflow improvement and waste reduction by preparing process visualization.

5.4. Case Code 22

Case code 22 [46] develops two prototypes of designed software interfaces that were invented and implemented within the context of BIM systems for facilitating the construction process. The software developed and presented in the article has several benefits, such as asynchronous communication, central information storage, and real access in main site management locations. Applying the Construction Hazard Assessment with Spatial and Temporal Exposure (CHASTE) model, BIM could assist individuals to access the safety resources such as examination, learning, and instruction of the required equipment at the right time. The systems by workflow improvement, visualization, and waste reduction enable clear process, transparent physical and managerial site state, doubt reduction, and more motivated workers who understand safety.

The scopes of the article are building fabrication, logistics, and installation on site. The method is through the development and testing of a software prototype. Considering the intersperse and dynamic physical environments and the typical broken contracting arrangements, BIM-based visualization interfaces are momentous for improving the transparency in construction.

6. Themes and Discussion on Recent Development on Digital Tools

Articles regarding lean and BIM were categorized into two groups, namely, interaction and adoption and implementation. The results of practitioners' opinions also were used to verify the findings of the systematic review and to present directions for future studies. Figure 7a shows the word cloud of the transcriptions referring to the main relevant concepts, which were discussed around lean and BIM in the interviews. One of the keywords is people, who are the center of a lean system, and they need to be properly engaged in the lean process [53]. Figure 7b,c shows the dominant keywords used in the documents published from 2018 to 2020 (a) and documents published from 2010 to 2013. The word cloud shows that the first order of key terms is BIM, lean, and design. The second order of keywords is in the project, people, process, and waste from the practitioners' perspective.

(a) (b) (c)

Figure 7. The main keywords of three main samples. (**a**) Practitioners' views, based on the transcriptions generated from their interviews, (**b**) the literature from 2018 to 2020, and (**c**) the literature from 2010 to 2012.

Figure 8 shows the results of cluster analysis based on the practitioner's interviews. Two main themes appeared in the figure, each constructed from two main branches of the cluster tree shown in Figure 8. The first theme focuses on factors relevant to lean and BIM integration concepts. Ohno [53] confirms that most of the previous studies focused on the theoretical aspects of BIM and lean. However, there are only a few practices of BIM-lean tool development [54]. While there are many advanced technologies available in the market, and a great demand for using them for lean purposes, there is a limited number of validated case studies using advanced technologies.

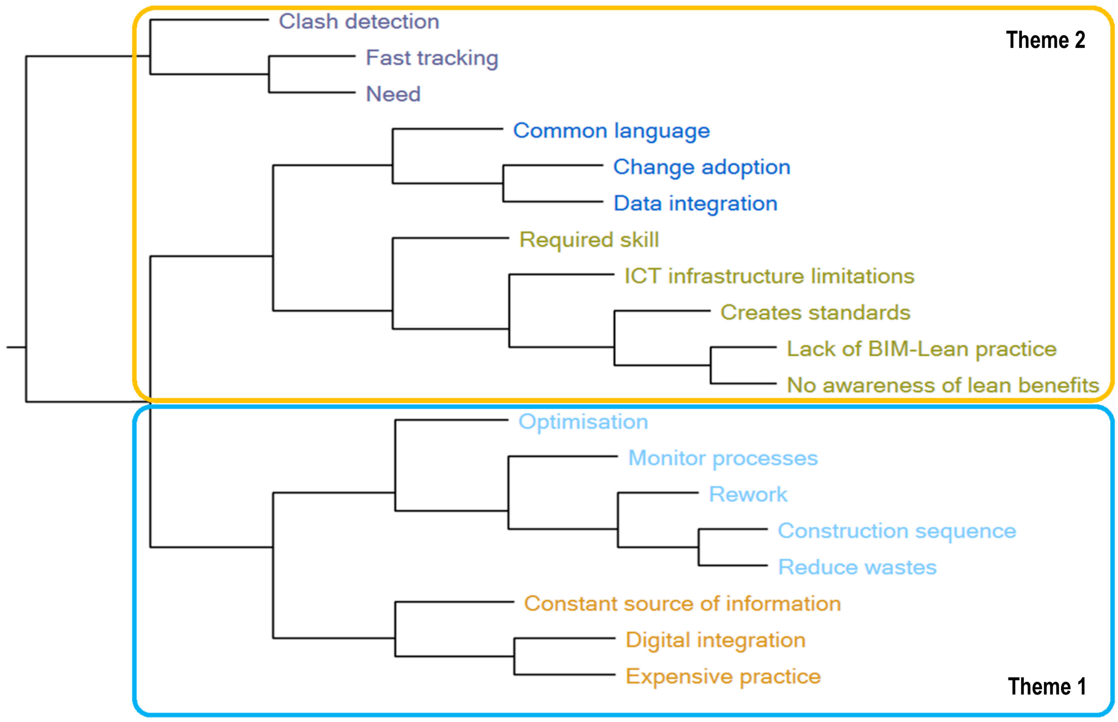
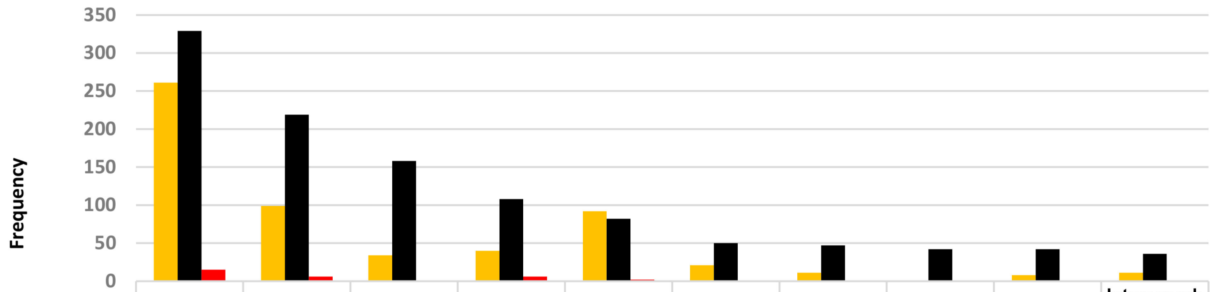


Figure 8. Themes of key concepts coming from the hierarchical clustering. Note: Two main themes appeared from the cluster analysis. Theme 1 refers to the integration of lean and BIM concepts; the second theme refers to lean-BIM adoption, including needs and challenges.

The second theme focuses on the need and challenges of lean-BIM applications in practice. This theme gives important insight into the barriers of the adoption process and mainly contributes to developing directions for future studies. While there is a rich literature on technology acceptance [55,56] and BIM adoption [57–59], there are a few systematic investigations of technology acceptance for lean purposes. Each theme will be discussed in Section 6.1 and Section 6.2 Figure 9 shows the frequency of themes and critical concepts discussed in three databases. The first database includes the articles identified in Search 2 (refer to Figure 1), but limited to the first 3 years of the decade (2010–2012). The last 3 years of the decade are also selected from the beginning of the decade to the end. The frequency of concepts and words within two periods helps identify if the scholars' concerns changed over the decade. Figure 9 shows that the concerns of BIM-lean concept adoption decreased at the end of the decade, and apparently, people are well aware of its advantages. However, the main concern would be small and medium enterprises (SMEs). Figure 9 also shows that other concepts received much attention, such as application development, big data, optimization, developing digital tools, and interoperability issues. Many current studies focus on the integration of these technologies for lean purposes [55,60]. These topics would most likely be continued in the following decade to address the practitioner's needs.



	Process	Value	Application	Waste	Adoption	Optimi*	LPS	Big Data	Digital	Interoperab*
2010-2012	261	99	34	40	92	21	11	0	8	11
2018-2020	329	219	158	108	82	50	47	42	42	36
Practitioners	15	6	1	6	2	1	0	0	1	0

Figure 9. A comparison of critical tools and concepts is frequently used in the early and late years of the decade based on the selected databases with the practitioners' interviews.

6.1. Theme I: Lean and BIM Interaction

Some articles studied the interaction between lean construction and BIM and implied that a synergy exists between them [61]. Using Structural Building Information Modeling (S-BIM), a flexible environment is provided for collaboration and data exchange with the related fields to Set-based Design (SBD) implementation. SBD is a lean design that shares information and cooperates with relevant fields to omit wasting elements and grows productivity in all phases of a project. SBD is based on S-BIM enables constructability and economic efficiency analysis to improve efficiency [23]. SBD provides for the use of a common language that enables processes to be effectively monitored by comparison against the standard (i.e., design).

The KanBIM concept is "a BIM-based lean production management system for construction." This system provides interfaces of site specific to cope with the construction project's limitation in managing the resource. KanBIM is a web-based collaborative interface that relates control to long-term plans and solves the controlling problem based on short-term decisions and vocabulary exchanges between managers and site teams. It is proposed that applying IoT standards for real-time task status report from the site can improve lean construction management systems such as KanBIM [47,62]. In the KanBIM concept [44], the use of visualization and pull-flow concepts incorporated into the project management processes enhances the ability to maintain flow and facilitate constant negotiations and commitments between teams.

One of the challenges to increase construction productivity is related to identifying the constraints, the resources of them, and the solutions for removing them. "A BIM-based technologically enhanced workflow" can be used to solve identified constraints and simplify the process of lean construction. Nath, Attarzadeh, Tiong, Chidambaram, and Yu [49] proposed a workflow to improve productivity by 36%. Increasing the flexibility and transparency, communication, and collaboration between the project participants can facilitate and synchronize the workflow properly, which can be attained using BIM tools to enhance the lean construction effects on productivity [49].

A new strategy for the design error management is presented by Al Hattab and Hamzeh [48], which is based on structures of the team, interplay dynamics, and diffusion or propagation of error. In the lean-and-BIM-based environment, the information flow and communication between the project stockholders are increased [63]. Thus, the application of lean and BIM for design error management reorganizes the design teams' structure and communication for early errors identification, duplication reduction, and error diffusion restriction. In lean-based systems, error-proofing or poka-yoke is traditionally a vital part of lean production systems, especially when mistakes have been happened before [48].

Therefore, lean-and-BIM-based environments have more potentials than traditional ones for detecting design errors and propagation diminishes [64].

KanBIM presents situational knowledge to individuals, guides them to execute the accurate pull workflow, reduces the rework and wasted time. Thus its application enables process flow improvement and waste elimination [48]. This is supported by responses from the expert interviews, where both lean and BIM present information that is accessible whenever it is needed. The information allows practitioners to monitor design processes and reduce "clashes" in scheduling.

Lean and BIM integration reduces the client's change in orders, minimizes redesign, and reduces variabilities and enables the predictability of project time, the process of construction, and the drawings and documentation accuracy of the construction process. Simultaneous usage of these two concepts enables optimizing the overall time and cost and increment of quality to a remarkable level [65]. As noted by our experts, BIM provides a constant source of real-time and accurate information that digitally enables work monitoring, rescheduling, and optimization. The literature identified several causes of waste in construction. For example, some of them are reported as a lack of clear goals and instructions for reducing waste, ineffective coordination and communication, and errors due to lack of details of design and construction processes [66]. Figure 10 shows the main factors related to lean-BIM based on the practitioners' opinions and verifies the finding of the present review. Figure 10 also shows key factors that should be considered in the construction industry, such as change adoption, developing relevant standards, and increasing the BIM-Lean practice in the industry.

The BIM adoption [29] helps construction projects to achieve their goals regarding better and greener outcomes and provides an information model to solve the challenges of low productivity issues and to gain favorable results [58]. The feasibility of prefabrication depends on BIM capability that may facilitate the supply chain's coordination, including all the stakeholders and vendors [67]. BIM is very important in the field of prefabrication as it prepares the facility of prefabrication scope management and off-site and on-site work packages coordination. The integration of lean and BIM can be effective for prefabrication, lean production, and supply chain implementation [68]. The adoption of a "common language" and "clash detection" shown in Figure 10 facilitates prefabricated construction processes.

Computer-aided tools for visualizing and facilitating processes can manage data effectively to make the state of the process clear to all stakeholders (refer to Figure 11), which is essential for advanced production management techniques implementation such as lean construction concepts [69]. Managing by seeing has been an important approach for lean systems [46], which would align with visualization tools provided by BIM systems.

Lean practices and BIM-based design can be effective in the design information flow. This new design management strategy relies on the dynamics of interactions and the accessibility of data to design teams. The design processes of lean and BIM can help design flow enhancement, the transformation of information, waste reduction, and generation of value [70].

The KanBIM system is applied for the control of workflow on site that brings together the process and the product information in a unified way, with an interface and embedded support of BIM for lean construction workflows. This system has potentially positive effects on the site personnel's ability to reduce wasted time. It can double the work scope that can be supervised reasonably [71].

The collective role of BIM and lean construction theory can improve the construction project cost control, improve the project efficiency, and diminish the activities that are not value added, or may maximize the project cost, or are not align with the customers' needs [72].

The virtual design and construction (VDC) method is applicable to BIM as a new approach to manage data and organize users and their work methods [73–76]. By implementing VDC and production management using lean methods, the achievement of performance improvement is possible. In the information flow phase, lean methods can be helpful for waste reduction within the VDC process. VDC enables the implementation of lean principles and incorporates management for waste elimination, costs reduction, productivity improvement, and projects' positive results creation [77].

Nodes

Name	Sources	References
Change adoption	2	4
Clash detection	2	2
Common language	4	7
Constant source of information	1	1
Construction sequence	2	2
Creates standards	3	3
Data integration	1	1
Digital integration	1	1
Expensive practice	2	2
Fast tracking	2	3
ICT infrastructure limitations	1	1
Lack of BIM-Lean practice	2	2
Monitor processes	1	2
Need	2	2
No awareness of lean benefits	2	3
Optimisation	3	5
Reduce wastes	4	18
Required skill	2	2
Rework	3	7

Figure 10. Key factors related to lean-BIM; identified based on the coding analysis on transcriptions. Note: source refers to the number of participants that referred to each factor. References are the total number of passages referring to one of the factors related to lean-BIM integration.

By reduction or reliable prediction of output variability, lean construction goals can be realized, and a BIM-integrated simulation framework can be used to plan reliable production and enhance the involved parties' efficiency in construction projects. Therefore, reliable production planning is significantly important for lean construction achievement [75].

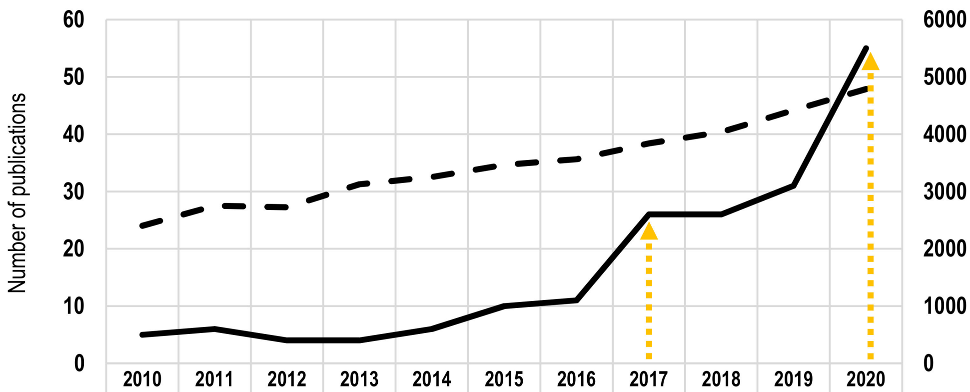
KanBIM system has a key role in individual decision support, coordination of team members, weekly negotiation about work plans, schematization granularity decrease to a diurnal level, real-time function restrictions assessment for calculating the task's maturity, and the language/action prospect implementation [78].

The experts verified the review findings in terms of the integration of lean and BIM. The results of the interview analysis showed that the role of stakeholders should be evaluated as a future direction. For example, an experienced practitioner stated:

> *"(a) User perspective of a lean design is that a person can move around an office environment or building seamlessly, and amenities are within a short distance.*
>
> *(b) Designer perspective is that they can reuse the objects created, and there are less clashes between disciplines. Inter-discipline coordination will be made much easier and less reliant on Integrated Design and Construction (IDC), which is a waste.*

> *(c) Construction Manager's perspective is that the construction methods can be streamlined to remove waste during the construction phase. This includes the following: Construction sequence, Material flow, Information flow, Logistics, Labor & machine utilization; common language to use is: Non-value-add (NVA), Value-add & Value efficiency analysis (VEA), Constructability, Efficiency, Cost reduction, Visualization."*

The stakeholder's role is significant since the network and the need for construction stakeholders are different from manufacturing, where was the origin of the lean concept. While BIM experts intended to explore how different stakeholders can commonly and collaboratively be coordinating and driving change [44,79], there is a gap in the literature investigating how lean guidelines can be implemented in the modeling process to consider all stakeholders benefits. In particular, future studies should explore and offer models on how sensors and IoT can generate data and update BIM so that stakeholders can update their lean strategies in a near real-time manner. The literature analysis (refer to Search 2 in Figure 1) shows that the number of studies investigating lean and digital technologies is increased. Figure 11 shows that there is a significant increase in 2017 and, most importantly, in 2020.



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Lean and Digital Technology	5	6	4	4	6	10	11	26	26	31	55
Lean	2404	2753	2726	3129	3253	3468	3565	3841	4040	4421	4790

Figure 11. A comparison between publications on lean and publications on lean and digital technologies (e.g., IoT, cyber-physical systems, BIM, or Digital Twin).

6.2. Cluster II: Lean and BIM Adoption and Implementation

A wide range of challenges in adopting and implementing BIM was identified, such as staff resistance to change, requirements of new workflows, less skillful people, a collaboration between internal and external stakeholders of the project, including architectures and engineers [80,81]. The review revealed that the key challenges of lean-BIM adoption and implementation could be addressed by addressing key factors such as the change persistence, improving the awareness of individuals on BIM potential values, adapting available workflows to lean related processes, training BIM utilization, providing the required hardware resources and infrastructure for BIM implementation, upskilling team members, and recognizing stakeholders' accountabilities. A bottom-up approach and top management support are needed for BIM implementation for individual engagement to use the prosperous strategies to reduce any possible persistence against change [45,81]. After all, in a lean system, people are the center of everything, and it is important that internal stakeholders be engaged in the process [45].

The concept of level of development (LOD) can develop BIM under the perspective of transformation, flow, and value (TFV) to manage the process of design based on the TFV theory and lean design management. The LOD framework makes it possible to apply design principles of lean via a practical usage of the TFV theory. The variables of LOD, the

LOD matrix, and the BIM models parametric character simplify the TFV theory and design workflow management integration in the BIM projects [53].

The main requirements for KanBIM performance are related to the subjects of the construction process conditions and its visualization of construction products, work manners visualization, planning support, discussion, feedback of obligation and situation, controlling the pull flow, workflow and consistency of plan, and manufacture experiments formalization to improve ongoing process [82].

Visual management (VM) as a strategy of visual communication is a basic part of lean production. BIM-based visual management implementation is limited in the construction industry. The significant barriers to the VM strategy must be carefully addressed. The awareness about the VM benefits should be increased, and the VM business case should be presented to quantify its benefits for more VM execution. Besides the quantitative benefits of VM, its qualitative benefits should also be identified [44].

The successful adoption of BIM depends on the prosperous alignment of BIM with work processes and readiness to project participant's coordination. The practices of lean construction meet the improving project team coordination and present some instructions for coordination enhancement. Lean practices decrease the issues of coordination in the project organization and provide the BIM adoption way [83].

Lean is regarded more as a philosophy or condition that is enabled by a set of tools such as Six Sigma. Womack, Jones, and Roos [84] defined lean as the pursuit of perfection for which continuous improvement techniques such as waste elimination are seen as vital tools. BIM, on the other hand, is a digital technology that can aid waste elimination. In Cluster I, lean and BIM can interact to create a constant source of information and may also facilitate process optimization, reduce waste, reduce rework, enables monitoring, and enables digitization, which, in turn, enables visualization. Cluster II summarizes how lean and BIM both create a common language that can facilitate adoption in organizations. It is also noted that rapidly advancing technologies in IoT can act as enablers in both clusters.

However, many practitioners are divided over how lean and BIM are integrated from the anecdotal evidence gathered from our expert interviews. From our interviews, it is noted that some practitioners see BIM as a separate construction field of knowledge, while most would acknowledge that there are some areas of knowledge overlap. Awareness is one of the key influential factors at the organizational level, and adoption of lean and BIM can only be successful if people within the organization are aware of its benefits. Previous studies presented relevant factors as an intention to use lean-BIM, communication behavior, relative advantage, compatibility, and social motivations [84]. As demonstrated in our literature review, there has been much research-specific areas of lean construction and BIM but much less on the benefits of a combined approach for these two concepts. Indeed, new technologies in IoT can act as an integrator of lean-BIM systems. IoT improves the process of generating information for lean purposes in an automated real-time manner in construction projects [28]. This gives significant opportunities for lean and BIM to be presented as an integrated framework where overlapping areas of knowledge and synergies can be explored in future research. For example, Akinade, Oyedele, Ajayi, Bilal, Alaka, Owolabi, and Arawomo [28] shows that an integrated cloud-based IoT tool can improve construction operation efficiency and facilitate the lean methods in prefabricated construction. However, the barriers of adopting and implementing the integrated systems of BIM-IoT for applying lean methods should be investigated specifically in different cases as future research. Figure 12 shows a set of critical components for lean construction and future directions of lean digital twinning.

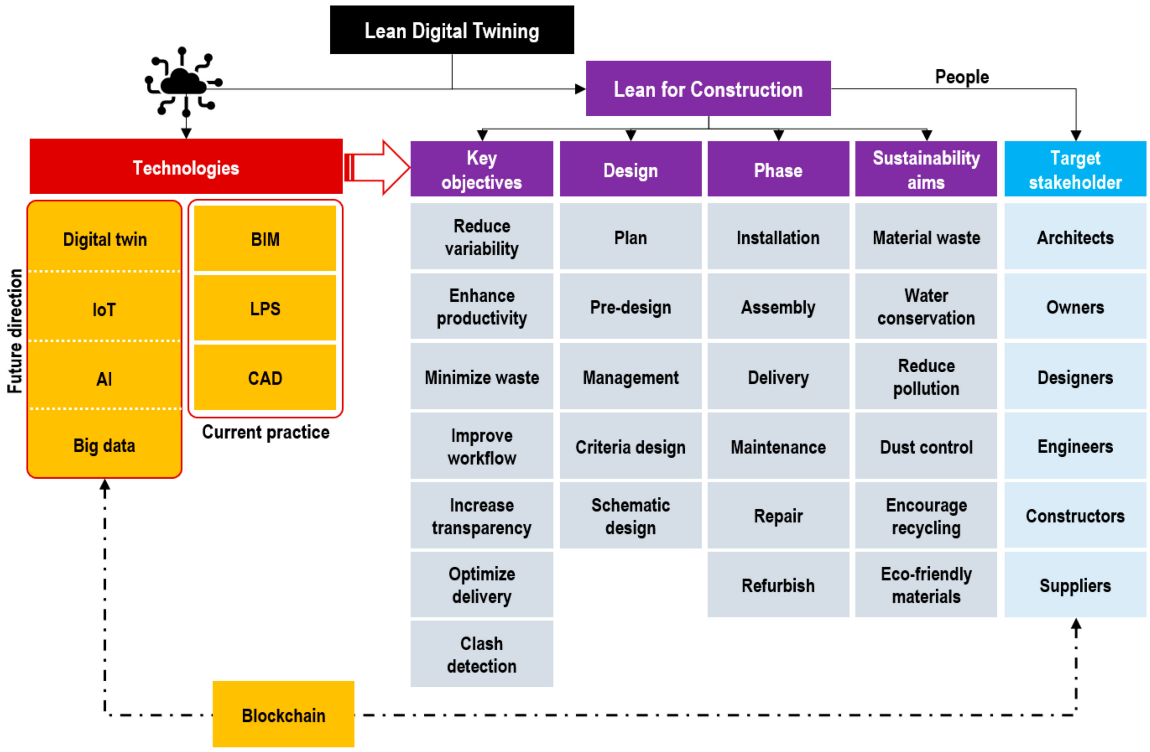


Figure 12. Digital Twining and relevant tools and components of lean construction. Note: BIM: Building Information Modeling; LPS: Last Planner® System; CAD: computer-aided design; IoT: Internet of Things; AI: artificial intelligence.

7. Conclusions and Recommendations

This investigation identified a significant gap in the literature and presented a set of directions for the interaction between lean and digital models in building and infrastructure construction. A mixed systematic analysis technique was adopted to find the most relevant and recent peer-reviewed articles focusing on lean construction and BIM. In addition, the thematic analysis was used to analyze the selected scholarly articles to explore the themes and processes that have been covered by pioneers. Expert opinions were also gathered to verify the findings of the current systematic review. We found that the interaction between lean and BIM has not been documented before 2009. The shift in themes and discussions in the early years of the last decade (2010–2013) and the last three years to the decade (2018–2020) were compared. In addition, a comparison was made between literature and expert opinions. The literature analysis shows that the literature shifted from the theoretical concepts of adoption to developing digital systems for achieving lean purposes. Recently, the combination of lean, BIM, and advanced digital technologies has been seen as an incremental trend in the published literature. However, among numerous related documents, only 48 articles mainly focused on the interaction of lean and BIM practices. Eight articles out of them have been cited more than 50 times, while the citations for 33 articles are less than that of 20. Findings revealed a large synergy between lean and BIM in control interactions and reduction in variations, and surprisingly there are many uncovered areas in this field, including the capability of IoT platforms. The number of published articles covering both lean and BIM with IoT is not many. There is a large clear gap in understanding synergetic interactions of the lean concepts and the combination of digital information and sensor-based technologies in specific fields of construction such as sustainable infrastructure projects, tunneling, mega projects, SMEs capability, and stakeholders' involvements. We suggest these topics and directions for future investigations.

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