Implementation of lean practices facilitated by BIM functionalities in the construction phase: advances and opportunities

Implementação de práticas lean facilitadas por funcionalidades BIM na fase de construção: avanços e oportunidades

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Abstract

Over the past few decades, construction productivity has been at a standstill. Lean and Building Information Modelling (BIM) is attracting increasing interest in the construction industry as a way to increase construction productivity. This paper aims to contribute to the body of knowledge by identifying hitherto unexplored opportunities for the use of BIM functionalities as a support and as facilitators of the application of lean practices in the construction phase. A systematic literature review was adopted as the methodological approach in this research, and reported case studies related to the scope of this paper were searched. The results show that lean practices can be classified into four degrees of BIM support based on the level of current exploration. Just one lean practice (the last planner system) has been extensively explored, three have been reasonably explored, and five have just been preliminarily explored. Five practices have not been explored at all. This research summarises the already studied and the potential additional uses of BIM functionalities to support each lean practice, showing that lean practices supported by BIM functionalities are still underused and that further studies can explore additional ways to support these practices. This study holds great value for a broader practical application of lean practices, bringing faster and easier results with more extensive BIM support.

Keywords: Building information modeling. Lean construction. Lean practices.

Resumo

A produtividade na construção civil está estagnada ao longo das últimas décadas. O interesse nas abordagens Lean and BIM tem crescido nos últimos anos, como forma de aumentar a produtividade na construção. O objetivo desta pesquisa é identificar oportunidades ainda não exploradas do uso de funcionalidades BIM como suporte e facilitadoras da aplicação de práticas lean. Foi utilizada a revisão sistemática de literatura como método da pesquisa. Os resultados do cruzamento das práticas lean e funcionalidades BIM indicaram 4 níveis de classificações de aplicações. Somente uma prática foi considerada muito explorada (last planner system), 3 foram consideradas razoavelmente exploradas e 5 pouco exploradas. 5 práticas foram classificadas como não exploradas. O trabalho conclui sumarizando os usos de funcionalidades BIM já explorados e os potenciais, para cada prática lean. As aplicações de funcionalidades BIM para apoiar práticas lean estão subutilizadas, o que indica que estudos adicionais podem ser feitos para apoiar mais algumas práticas. Isso pode ser de grande valor para uma aplicação mais ampla das práticas lean, trazendo resultados mais rápidos e fáceis, com suporte BIM mais amplo.

***Palavras-chave**: Building information modeling; Lean construction; Práticas lean.*

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Introduction

Construction productivity has remained practically stable over the past few years, while productivity in other industries has more than doubled (TEICHOLZ, 2013). If construction productivity were to catch up with the total economy, the industry's value added could rise by $1.6 trillion a year (2% of global GDP) (MCKINSEY, 2017). This scenario motivates the use of several approaches that aim to improve sector productivity, including lean and BIM (building information modelling).

Lean thinking emerged in the automotive industry and has proven to have a positive effect on improving productivity by focusing on the elimination of waste and the provision of value to end customer. Its application has spread to different sectors, including construction, with decades of studies and cases (KOSKELA, 2000).

As a digital shared knowledge resource, BIM has changed the way information flows among construction agents, having a significant impact on productivity improvement (POIRER; STAUB-FRENCH; FORGUES, 2015; LIN *et al.*, 2017).

Both approaches, lean and BIM, are attracting increasing interest in the construction industry. Their development in the sector has followed specific and independent pathways, with scarce connections in the early stages. As these concepts have become more adopted, the possible synergies between these approaches have started to be explored, and the use of BIM as a lean implementation facilitator has attracted interest.

Some authors discuss the combination of these two approaches, such as the seminal discussion about the synergies between them presented by Sacks *et al*. (2010). These authors analyse the relationship between BIM and lean principles, providing an important conceptual and theoretical framework for this analysis. One can identify as a knowledge gap the lack of a more detailed analysis of the synergies between lean and BIM, where lean principles are deployed in lean practices, which could facilitate even more practical applications.

For sustainable lean implementations, people must understand lean principles and select the best way to use the lean practices that are needed in their environment and for their business needs (PICCHI; GRANJA, 2004). Lean practices (concepts and tools, such as Kanban and standardised work) are used to implement lean principles, translating lean principles into routines for the job site. Facilitating such practices through BIM will provide important support for the dissemination of lean.

If we consider the project phase on which studies have focused, another knowledge gap in this discussion can be identified. Santos, Costa and Grilo (2017) pointed out that studies on BIM and construction management have increased over the years but are still scarce compared to studies on other areas, such as design. Lean, on the other hand, presents more applications in the construction phase than in other phases (PICCHI; GRANJA, 2004).

This paper aims to contribute to the body of knowledge by identifying hitherto unexplored opportunities for the use of BIM functionalities as a support and as facilitators of the application of lean practices in the construction phase.

Other authors have discussed the synergies between lean and BIM, but this study focuses specifically on the construction phase and offers a new view, considering lean practices deployed based on lean principles. This approach aims to identify gaps in the use of BIM to facilitate specific and fundamental lean practices, seeking to make contributions with a closer connection to practical applications.

To achieve the stated aim, fundamental lean practices and BIM functionalities were characterised based on the literature. Then, a systematic literature review was performed, in which research on lean and BIM in the construction phase was searched. Finally, a cross-reference analysis was conducted to identify lean practices that have already been supported by BIM functionalities in the literature as well as gaps.

Background: lean practices and bim functionalities

In this section, we present a summary of the fundamental lean practices and BIM functionalities that will be used for cross-reference analysis.

Lean Practices

Lean thinking follows some key concepts based on the Toyota production system (TPS). The five lean principles proposed by Womack and Jones (1996) are still a useful reference for understanding the concept:

value, the value stream, flow, pull and perfection. Some authors, such as Picchi and Granja (2004), Alves *et al*. (2009), Miranda Filho, Heineck and Costa (2016) and Tezel and Aziz (2017a), have described the main lean practices applied to the construction phase by referring to the lean principles. Based on these studies, Table 1 presents the main lean practices and some practical examples of their use in construction with the respective context. Value to the customer is the first lean principle and is not included in Table 1 since it is considered a driver of all the other principles, as well as the basis of leadership values, mindset development and the waste elimination focus.

BIM functionalities

BIM is a methodology for digitally managing design and construction throughout the entire building life cycle (PENTTILÄ, 2006). This methodology has several design and construction functionalities (SACKS *et al*., 2018). According to Sacks, Radosavljevic and Barak (2010) and Sacks *et al*. (2018), when applied to the construction phase, the most relevant BIM functionalities are those presented in Table 2, which provides a brief description of each functionality.

Table 1 - **Main lean practices and examples of application in construction**

Lean principle	Lean practice	Examples in construction	
		Reference	Context of application
VALUE STREAM	VSM (value stream map)	Yu *et al*. (2009) and Rosenbaum, Toledo and González (2014)	Value stream mapping is used to develop a lean model for house construction
FLOW	LPS (last planner system)	Ballard and Howell (2003) and Formoso and Moura (2009)	LPS is implemented in different project types
	Line of balance	Arditi, Tokdemir and Suh (2002) and Kemmer *et al*. (2008)	The line of balance is applied in multistorey buildings
	Andon	Kemmer *et al*. (2006) and Biotto *et al*. (2014)	Andon is applied in facility construction using mobile devices
	Poka-yoke	Santos and Powell (1999) and Tommelein (2008)	Many types of poka-yoke have been presented as examples in construction and design
	Production cell	Santos, Moser and Tookey (2002) and Mariz *et al*. (2013)	Production cells are applied in drywall and foundation activities
	Standardised work	Mariz *et al*. (2013), Fernandes *et al*. (2013) and Saggin *et al*. (2017)	Standardised work is implemented in foundation and waterproofing activities
	Small batch	Ward and McElwee (2007) and Bulhões, Picchi and Granja (2005)	Small batches are applied in nonrepetitive projects
PULL	Kanban	Arbulu, Ballard and Harper (2003) and Khalfan *et al*. (2008)	The adoption of Kanban integrates an external supplier
	Heijunka	Carneiro *et al*. (2009) and Barbosa *et al*. (2013)	A Heijunka box is applied to level mortar production in the job site
	Takt time	Bulhões, Picchi and Granja (2005) and Mariz *et al*. (2012)	Takt time is adopted for ceramic tiling
PERFEC-TION	Daily management	Binniger *et al*. (2017)	Daily management is applied in a project manager routine
	5S	Tezel and Aziz (2017b)	5S is implemented in highway construction and maintenance
	Kaizen event	James, Ikuma and Nahmens (2014)	Kaizen events occur in modular home manufacturing

Table 2 - **Main BIM functionalities for the construction phase**

BIM functionality	Description
3D Visualisation	Allows the visualisation of construction dimensions, aesthetics and form, making the design intelligible in the context of the construction site, especially for non-specialists or staff without much expertise (SACKS *et al*., 2010)
4D Modeling	This is the result of integrating 3D with the time variable, considering project planning (RILEY, 2005; STAUB-FRENCH; KHANZODE, 2007); makes it possible to simulate the construction process by considering the step-by-step progress of the construction (SACKS *et al*., 2018)
SCP – Simulation of the construction process	Adds temporary resources (cranes, concrete mixers, scaffolding, etc.) and conducts discrete event simulation with a mode for testing construction plans and project logistics (SACKS *et al*., 2010); different technologies can be used to support the simulations, e.g., laser scanning, GPS and RFID tags (SACKS *et al*., 2018)
5D Modelling	Automated cost estimation that allows the instant generation of cost budgets, adding quantified cost information to the model and facilitating project management and financial monitoring (KAMARDEEN, 2010)
VPS – Visualisation of the process status	Enables the visualisation of the execution status of a project's services, following a parametric model and enabling better visual control (DAVE; BODDY; KOSKELA, 2011); uses devices that allow remote control of the evolution of the job site, identifying activities that are ready to start, are in progress, have stopped or have been completed (SACKS *et al*. 2010)
OP/PC – Online process/product communication	The use of information technology and mobile devices to track and update project information (SACKS *et al*., 2018)

Research method

The research strategy adopted was a systematic literature review (SLR). This strategy aims to aggregate the main existing evidence with regard to a particular research field and to point out gaps for future studies (BRERETON *et al*., 2007; KITCHENHAM *et al*., 2009). Separate SRL studies have been carried out for both BIM (SANTOS; COSTA; GRILO, 2017; LU *et al*., 2015; CHENG; LU; DENG, 2016) and lean construction (BAINES *et al*., 2006; VIANA; FORMOSO; KALSAAS, 2012: REYES, 2015).

The systematic literature review was conducted in four steps, as proposed by Morandi and Camargo (2015):

(a) defining the research question;

(b) defining the search strategy (search string, year range and sources of publications);

(c) starting the searches and refining the quantity of papers using predefined criteria; and

(d) analysing and concluding.

Definition of the research question

BIM and lean thinking were chosen as the main topics. Previous authors have studied the synergies between lean and BIM in all phases. The construction phase of the construction life cycle was defined as the focus of this study.

Based on an initial literature review, some of the main lean practices and BIM functionalities applied to the construction phase were identified.

Thus, the research question was defined as follows: "What are the hitherto unexplored opportunities for using BIM functionalities as facilitators of the implementation of lean practices in the construction phase?".

Research strategy

The first stage of the review was database selection. The Scopus and Compendex databases were chosen, as well as the proceedings of the IGLC (International Group for Lean Construction) Conference. After some

testing, the search terms (string) used in the database were formulated: "(Lean and BIM) and (construction or building)", "(Lean and building information modeling) and (construction or building)", and "(Lean and virtual design and construction) and (construction or building)".

Regarding the proceedings of the IGLC Conference, the search was carried out using the string "BIM" or "building information modeling" or "virtual design and construction" since these proceedings specialise in lean construction.

The searches included articles published from 2003 to 2019.

Searches and encoding (bibliometric data)

The initial search resulted in a total of 532 articles. Then, a title analysis selected just the papers related to the construction phase, resulting in 250 studies. Duplicate articles were excluded (30 articles), and papers analysis based on reading the abstracts (107 articles), and full papers (80 papers) excluded the studies that did not actually meet the criteria for selection, resulting in 43 studies. The snowball method (references collected from the selected articles) was also adopted, which resulted in the addition of 6 articles, for a total of 49 studies selected. Figure 1 shows the numerical data for each stage of the refinement process.

The criteria for paper selection were as follows:

(a) papers having a practical application (case studies);

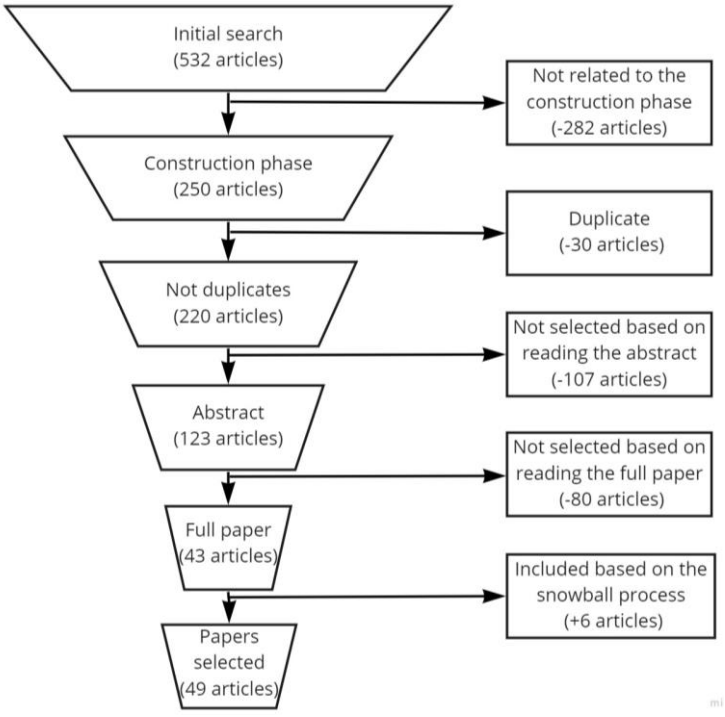
(b) literature review articles were considered just as a source for primary studies; and

(c) papers presenting the joint application of BIM functionalities and lean practices.

Thus, papers that applied lean practices and BIM functionalities separately were not considered.

Bibliometric data on the selected articles were then collected. The year of publication, sources of publication and types of projects were included in the data analysis.

Figure 1 - **Bibliometric data on the selected articles**



Synthesis of the results

A cross-reference matrix was organised to show the combinations of lean practices and BIM functionalities already discussed in the literature and the research gaps indicating additional potential opportunities for combinations. The analysis discussed the potential contributions of BIM functionalities to each lean practice, identifying the current state and possible advances.

Ultimately, final considerations about the main opportunities for future applications were made.

Results and discussion

Bibliometric Analysis

Based on the selected studies, Figure 2 presents the number of publications over the period of study, which ranged from 2003 to 2019.

Figure 2 shows that the number of papers based on the selection criteria has increased over the last ten years. One hypothesis is that this increase is due to the increased use of BIM, which was in the early stages at that time.

Table 3 shows the sources of publication of the selected papers related to BIM functionalities supporting lean practices, organised by the focus of the publication (journals, books, or abstracts).

In Table 3, all 49 publications collected refer to research on lean and BIM. Over 50% of the selected articles (26 searches) were published in lean-specific research sources (the IGLC Conference and Lean Construction Journal). Nine selected studies were published in construction management journals, and 14 studies were from sources related to the area of technology in construction.

The most frequent source of the selected articles is the proceedings of the IGLC Conference (25), which is a publication that specialises in lean. The reason for the concentration of selected papers in this source is probably the pioneering paper about the synergy between lean and BIM published in the proceedings of the 2009 IGLC Conference by Sacks *et al*. (2009), which subsequently generated Sacks *et al*. (2010). Since the publication of these papers, lean and BIM have been permanent themes at the annual IGLC Conference.

On the other hand, the second most frequent source is Automation in Construction (7), which focuses on technology, and both Engineering, Construction and Architectural Management (2) and Journal of Construction Engineering and Management (2) are the third most frequent source.

As well as these four sources with the most selected articles and the 2 books, 11 different journals publishing a total of 11 papers are present in the selection, showing that interest in the subject has spread to different research forums related to lean, management and technology.

Figure 2 - **Number of publications over the period of study**

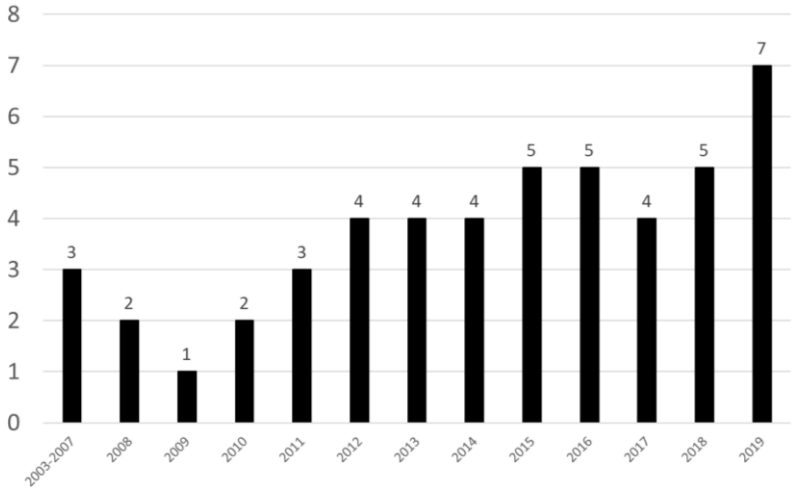


Table 3 - **Source of publication related to BIM functionalities supporting lean practices in the construction phase**

Publication	Number of papers	Publication focus	Paper subtotals by publication focus
IGLC Conference	25	Lean	26
Lean Construction Journal	1		
Engineering, Construction and Architectural Management	2	Management	9
Journal of Construction Engineering and Management	2		
Implementing lean in construction: Lean construction and BIM*	1		
Canadian Journal of Civil Engineering	1		
Construction Management and Economics	1		
Construction Research Congress	1		
International Journal of Construction Management	1		
Automation in Construction	7	Technology	14
BIM Handbook*	1		
Computing in Civil and Building Engineering	1		
Construction Innovation	1		
Electronic Journal of Information Technology in Construction	1		
Journal of Computing in Civil Engineering	1		
Journal of Mathematics Science and Technology Education	1		
The Open Construction and Building Technology Journal	1		
TOTAL	49		49

Note: *books were included based on the snowball method.

Love (2002) classifies the types of building projects as residential buildings, medical centers, commercial buildings, schools, public facilities and industrial buildings, and Cheng, Lu and Deng (2016) classify the types of infrastructure projects as bridges, roads, railways, tunnels, energy infrastructure, power generation, oil and gas, mines, utility infrastructure, utility infrastructure, recreational facilities, water management infrastructure, airports, ports and harbours. Based on this classification, an adaptation was made to identify the types of projects on which the selected articles focused (Figure 3).

Figure 3 shows a large concentration of applications in building projects, specifically in residential buildings and medical centers. On the other hand, there are few applications in civil infrastructure projects. BIM functionalities and lean practices have not yet been applied in some types of projects, such as bridges, tunnels, energy infrastructure, energy generation, mines, public facilities, recreational facilities, and water management infrastructure. This analysis provides insights for possible future applications.

Data cross-checking: BIM functionalities vs. Lean practices

The 49 selected papers were analysed and are identified in Table 4, which represents the cross-checking of content related to BIM functionalities and lean practices.

Emerging classification of the degree of application

Table 4 shows that a clear differentiation of lean practices emerges based on the degree of reported application of BIM functionalities. For example, LPS was referred to in 43 articles, while four lean practices were not mentioned at all.

Observing Table 4, we adopted a classification based on the number of selected papers per lean practice. One lean practice has been extensively explored (43 papers), three have been reasonably explored (7 to 9 papers), five have been preliminarily explored (1 or 2 papers), and five are currently unexplored (zero papers). The lean practices for each classification are shown in Table 5 and are discussed below.

Figure 3 - **Project types**

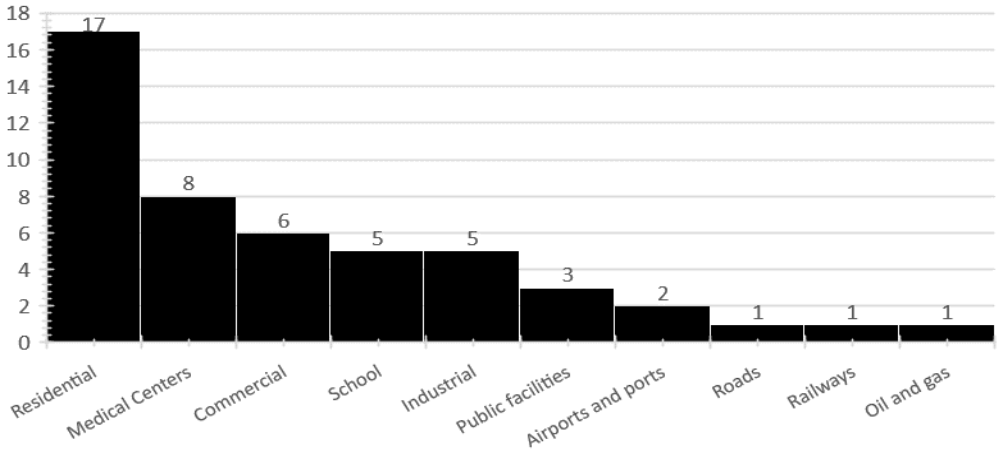


Table 4 - **Cross-checking of the relationships among BIM functionalities and lean practices in the construction phase based on the literature**

	LEAN THINKING PRINCIPLES															
	VALUE STREAM	FLOW							PULL			CONTINUOUS IMPROVE-MENT			Number of practices	Number of papers
Lean practices / BIM funciona-lities	VSM	Last planner system	Line of balance	Andon	Poka-yoke	Production cell	Standardized work	Small batch	Kanban	Heijunka	Takt time	5S	Kaizen event	Daily management		
3D Visualisati-on	[23,24]	[2,3,6,8,9,10,11,12,13,16,18,19,22,26,28,29,30,31,32,33,34,35,36,39,44,46,47,48,49]		[8,9,11, 18, 25,26,46]	[2]			[25]	[8,9,11, 18, 25,26,46]		[25]		[1]		9	33
4D		[3,4,5,7,10,14,16,17,20,21,22,27,38,39,40,45,46,49]	[5,7,12, 21,37,41,42,43, 48]												2	24
5D		[5]	[5]												2	1
Visualisati-on of process status (VPS)		[2,5,6,8,9,15,16,17,25,26,32]		[8,9,11, 18, 25,26]	[2]			[25]	[8,9,11,25,18,26]						5	13
Online process/ product communi-cation (OPPC)		[2,6,8,9,10,11,15, 16,18,25,26,30,31,46]		[8,9,11, 18, 25,26,46]	[2]			[25]	[8,9,11, 18, 25,26]						5	14
Simulation of the constructi-on process (SCP)		[5,7,12,13,19,22, 30]	[7,12]												2	7
Number of funciona-lities	1	6	3	3	3			3	3		1		1			
Number of papers	2	43	9	7	1			1	7		1		1			

Note: Caption: 1 Sacks *et al.* (2018); 2 Dave, Boddy and Koskela (2011); 3 Bhatla and Leite (2012); 4 Hyatt (2011); 5 Scheer *et al.* (2014); 6 Dave *et al.* (2013); 7 Bortolini, Shigaki and Formoso (2015); 8 Sacks *et al.* (2011); 9 Sacks *et al.* (2012); 10 Ibarra *et al.* (2016); 11 Liu and Shi (2017); 12 Ben-Alon and Sacks (2015); 13 Clemente and Cachadinha (2013); 14 Dave *et al.* (2013); 15 Dave *et al.* (2014); 16 Dave *et al.* (2016); 17 Gerber, Gerber and Kunz (2010); 18 Gurevich and Sacks (2014); 19 Hamdi and Leite (2014); 20 Harris and Alves (2013); 21 Kemmer *et al.* (2016); 22 Mahalingam, Yadav and Varaprasad (2015); 23 Moghadam, Alwisy and Al-Hussein (2012); 24 Nath *et al.* (2015); 25 Sacks, Treckmann and Rozenfeld (2009); 26 Sacks, Radosavljevic and Barak (2010); 27 Sriprasert and Dawood (2003); 28 Tillmann and Sargent (2016); 29 Toledo, Olivares and González (2016); 30 Wen (2014); 31 Fosse, Ballard and Fischer (2017); 32 Von Heyl and Teizer (2017); 33 Zeng, König and Teizer (2017); 34 Zhang *et al.* (2018); 35 Koseoglu and Gunes (2018); 36 Matta *et al.* (2018); 37 Vargas, Bataglin and Formoso (2018); 38 Bataglin *et al.* (2019); 39 Heigermosera *et al.* (2019); 40 Koseoglu, Sakin and Arayicy (2018); 41 Staub-French, Russel and Tran (2008); 42 Jongeling and Olofsson (2007); 43 Björnfot and Jongeling (2007); 44 Wang *et al.* (2016); 45 Bortolini, Formoso and Viana (2019); 46 McHugh, Dave and Craig (2019); 47 Dallasega *et al.* (2019); 48 Gómez-Sánchez, Ponz-Tienda and Romero-Cortés (2019); and 49 Álvares and Costa (2019).

Extensively explored practice

The last planner system (LPS) appears in Tables 4 and 5 as the only lean practice with applications of BIM functionalities that, to date, has been extensively explored. Mentioned by 43 articles, LPS was applied for all six BIM functionalities discussed. This result is probably a consequence of the fact that LPS has been one of the most commonly used lean practices in construction for a long period of time.

Ibarra *et al*. (2016) used LPS integrated with Autodesk 360 to track a project's progress and to carry out quality control. Bhatla and Leite (2012) proposed a framework for integrating BIM and LPS, while Tillman and Sargent (2016) investigated opportunities for further integrating BIM and LPS. Toledo, Olivares and González (2016) analysed 2 project cases: one using only an LPS and another employing an LPS integrated with BIM. The authors concluded that the LPS integrated with BIM provides better results and several benefits. Kemmer *et al*. (2016) analysed the use of the last planner system and 4D modelling in a retrofit project as a means of reducing the interruption of property usage. Bortolini, Formoso and Viana (2019) applied LPS and 4D to simulate logistics in an industrial plant.

Workflow systems, such as Lewis (SRIPRASERT; DAWOOD, 2003), KanBIM (SACKS; RADOSAVLJEVIC; BARAK, 2010) and VisiLean (DAVE *et al*., 2011), use LPS to assist in project management, employing BIM to make it more visual. When associated with a parametric model and PPC (planning and production control) activities, work control becomes faster and intuitive.

Based on an analysis of the five macro steps of the last planner system, i.e., milestone planning, phase planning, make-ready planning, commitment planning and daily huddles (BALLARD; TOMMELEIN, 2016; EBBS; PASQUIRE, 2019), there is a large concentration of applications in make-ready planning and commitment planning. This result suggests that there are opportunities to explore the other macro steps, especially daily huddles, and it demonstrates that even though the LPS has, to date, been the most studied lean practice considering BIM support, it can be further enhanced by using BIM functionalities in all of its macro steps.

Reasonably explored practices

Table 5 shows that three lean practices have been reasonably explored by a considerable number of papers, i.e., 7 to 9. These practices are the line of balance, Andon and Kanban.

Articles related to the line of balance focus on three BIM functionalities: 4D, 5D and simulation of the construction process. In contrast, articles about Andon and Kanban concentrate on the other three BIM functionalities: 3D visualisation, visualisation of the process status, and online process/product communication.

This result suggests that some lean practices demand functionalities that are more adequate for planning and simulation (4D, 5D and simulation of the construction process), while others need support from functionalities that are more related to visualisation and communication (3D visualisation, visualisation of the process status, online process/product communication).

Table 5 - **Degree of application of BIM functionalities in lean practices**

Number of papers	**Degree of reported applications of BIM functionalities**			
	Extensively explored	**Reasonably explored**	**Preliminarily explored**	**Not explored**
	43	7 to 9	1 or 2	0
Lean practices	Last planner system	Line of balance	VSM	Production cell
		Andon	Poka-yoke	Standardised work
		Kanban	Small batch	Heijunka
			Takt time	5S
			Kaizen event	Daily management
Number of lean practices	1	3	5	5

Ben-Alon and Sacks (2015) used agent-based simulation (ABS) to simulate the execution of some activities, demonstrating their results through a flowline (a concept related to the line of balance). Jongeling and Olofsson (2007), Björnfot and Jongeling (2007), Staub-French, Russel and Tran (2008), Scheer *et al*. (2014) and Bortolini, Shigaki and Formoso. (2015) used a line of balance as the basis for 4D planning, demonstrating the potential gains of this interaction for planning visualisation and interference identification.

Andon and Kanban appear frequently due to their use in the KanBIM workflow system, which employs these practices to signal the execution status of activities in a project.

"4D modeling" is concentrated in just 2 lean practices (the line of balance and last planner system), indicating its strong relationship with these two practices. This result demonstrates the importance of combining BIM and planning techniques (SEPPÄNEN; MODRICH; BALLARD, 2015); however, such combinations could still be enhanced through 4D modeling.

Lewis, KanBIM, and VisiLean integrate BIM functionalities with LPS, Andon, and Kanban. Additional software connections could use line of balance with 4D, offering more planning options.

This group of practices has already been the subject of discussions of applications of BIM functionalities by different authors, but there could be additional opportunities for exploration, as discussed in the next section.

Preliminarily explored practices

Tables 4 and 5 show that five lean practices were mentioned in only 1 or 2 articles. These practices are VSM, poka-yoke, small batch, kaizen events, and takt time.

These studies can be considered pioneers, leaving plenty of opportunities for further exploration. For example, only poka-yoke was mentioned regarding three BIM functionalities (3D, VPS, OP/PC); the other four lean practices in this group were discussed only for 3D visualisation applications. Several other potential applications for supporting these practices can be identified, as discussed below.

Takt-time is a fundamental lean concept that aligns the production rhythm to customer demand, and in the construction context, it has been associated with the planning stage (FRANDSON; BERGHEDE; TOMMELEIN, 2013) and with potential relationships with 4D simulation parameters.

The application of the small batch concept is strongly associated with continuous flow and has also been used in construction in the planning phase (DLOUHY; BINNINGER; HAGHSHENO, 2019). These practices can also be used in planning software that is facilitated by the integration of BIM functionalities, especially 3D, 4D and SCP, allowing different scenario simulations with better visualisation to make faster decisions.

Kaizen events and VSMs can be applied at any stage of the construction phase. BIM functionalities could optimise data collection and processing.

Not explored practices

Five practices – production cells, standardised work, Heijunka, 5S and daily management – have no mentions in the selected papers.

These practices are frequently mentioned by practitioners and researchers as fundamental elements for the implementation of lean principles, and the lack of research on these practices with regard to applications of BIM functionalities reveals a major opportunity.

Heijunka could also be implemented in the planning phase to level production and resources. 3D, 4D, and SCP would facilitate this practice.

5S, production cells and standardised work could use 4D and SCP to simulate the micro planning of construction activities, detailing the design of the work layout, stock location, material movement routes, etc.

Daily management could be supported by the optimisation of data collection at the construction site using online process/product communication and visualisation of process status.

Auxiliary technologies

Tezel and Aziz (2017a) proposed some auxiliary technologies that can enhance the use of BIM:

(a) mobile computing & wearable devices;

(b) the Internet of Things (IoT);

(c) context-aware systems;

(d) AutoID (RFID); and

(e) virtual and augmented reality systems; and surface scanning (laser scanning, photogrammetry).

Table 6 presents the use of these auxiliary technologies to enhance the synergies between BIM functionalities and lean practices based on the literature.

Auxiliary technologies are mentioned in 19 papers. The most mentioned auxiliary technology is mobile computing (16), mainly due to the use of mobile devices (tablets, cell phones).

Other technologies have been little explored. For example, Dave *et al*. (2016) used the IOT, and Wang *et al*. (2016) used RFID connected to a 3D BIM model to control material constraints. Virtual reality CAVEs (virtual and augmented reality systems) have been used to guide the performance of "virtual" work in a building with sixteen apartments (GUREVICH; SACKS, 2014). Touchscreen TVs integrated with BIM that are used in job sites are mentioned as resources for employee communication (SACKS *et al*., 2011; LIU; SHI, 2017).

Discussion

Table 7 summarises the applications found in the literature and the potential applications, as discussed in the previous sections. For all lean practices, interesting additional combinations can be observed, demonstrating that the synergies between lean and BIM have large room for further development.

Table 6 – **Auxiliary technologies that enable BIM and lean interaction**

Authors	Mobile computing (& wearable devices)	The Internet of Things (IoT)	Context-aware systems	AutoID (RFID, NFC)	Virtual and augmented reality systems	Surface scanning (laser scanning, photogrammetry)
Dave *et al*. (2013)	x		x	x		
Sacks *et al*. (2011)	x					
Sacks *et al*. (2012)	x					
Ibarra *et al*. (2016)						
Liu and Shi (2017)	x					
Dave *et al*. (2014)	x	x				
Dave *et al*. (2016)	x	x	x	x		
Gurevich and Sacks (2014)					x	
Hamdi and Leite (2014)	x					
Sacks, Radosavljevic and Barak (2010)	x					
Sriprasert and Dawood (2003)	x					
Tillmann and Sargent (2016)	x					
Fosse, Ballard and Fischer (2017)	x					
Von Heyl and Teizer (2017)	x	x				
Zhang *et al*. (2018)	x					
Koseoglu and Gunes (2018)	x					
Koseoglu, Sakin and Arayicy (2018)	x					
McHugh, Dave ad Craig (2019)	x					
Álvares e Costa (2019)						x
Total	16	3	2	2	1	1

Table 7 – **Lean practices supported by BIM functionalities – application and suggestion for future research**

Lean Practices	Already Applied	Opportunities for future applications
Last planner system	The last planner system is the lean practice with the most interactions with BIM functionalities. There is a great concentration of applications supported by 3D visualisation and the 4D functionality. Analysing the 5 steps of the last planner system (BALLARD; TOMMELEIN, 2016; EBBS; PASQUIRE, 2019), we noticed that make-ready planning and commitment planning are the steps with the most applications of BIM functionalities.	5D can be associated with a last planner system to aid decision making. 3D, 4D, and visualisation of process status can be used in milestone planning, phase planning, and daily huddles to facilitate visualisation of completed and planned activities.
Line of balance	Software programs are using 4D and simulation of the construction process with the line of balance to enable work progress visualisation. Thus, it is possible to plan work by location, simulate the workflow, and through the model see the progress and potential team interfaces in a clearer and easier way.	Only one article presented a connection with 5D, providing an opportunity for exploration in further studies. In addition, lean integrated planning methodologies could be enhanced by BIM functionalities, especially 4D, simulation of the construction process and visualisation of process status.
Andon	Some workflow management systems use the Andon concept to identify the production status using a virtual model. Some statuses used by such systems are no entry (wait to mature), future (wait for the planned start date), can be started, work in process, stopped, completed and go again (SACKS *et al*., 2011).	Online process/product communication is a functionality that has a significant connection with Andon. Andon can be applied to report machines, equipment, and production status through mobile devices and the internet.
Kanban	The Kanban concept used in the selected articles is associated with the work-in-progress status using a virtual model. In other words, through virtual information, the workflow management system provides information to the production teams on the activities that can be initiated.	Online process/product communication functionality can be applied to control the consumption status and track the positioning of materials on the job site with a virtual model.
VSM	VSM has been used together with BIM to facilitate modular and prefabricated construction. Additional steps and rework have been identified by CAD drawings; thus, with the implementation of VSM and 3D visualisation, there is an increase in the productivity gains of production teams.	Simulation could be performed to understand the current state and mainly to design the future state. Several possible scenarios could be produced through simulation of the construction process and 4D.
Poka-yoke	The poka-yoke concept has been used to prevent starting tasks that are not ready to start in the VisiLean (workflow management system); thus, the button to start an activity is available only when all the requirements for starting are met (DAVE *et al*., 2011).	Poka-yoke could be applied using sensors that turn machines off when a problem occurs. The online process/product communication functionality could aid in this application.
Small batch	Small batches have been used to update the construction status using a board. They have been used to update a system every 10 minutes in the model. Small batches have been integrated with the online process/product communication functionality (DAVE *et al*., 2016).	Small batches are a practice with wide applicability since use in macro planning until execution and control phase can be facilitated by several BIM functionalities (3D, 4D, and simulation of the construction process).
Takt time	Takt time has been used in KanBIM. When any status duration is longer than the takt time, it indicates bottlenecks in the model (SACKS; TRECKMANN; ROZENFELD, 2009).	Planning software could use takt time to simulate different scenarios and for a better visualisation for faster decision making (3D, 4D, and simulation of the construction process functionalities).
Kaizen event	Kaizen events have applied 3D visualisation to improve constructability in an automotive factory. The results were waste and cost reductions (SACKS *et al*., 2018).	Kaizen events can be used to solve any type of problem and at any construction stage.
Production cell	-	3D, 4D, and simulation of the construction process simulations could be performed to define teams' work layout, logistics and inventory positioning.
Standardised work	-	4D and simulation of the construction process can be used for micro planning and training of production workers.
Heijunka	-	Heijunka can be used in planning software to balance and level resources, which can be aided by 3D visualisation and 4D simulation.
5S	-	5S can be used to assist in the elaboration of the construction site layout (including additional elements, such as supply routes, places to store equipment, warehouse, etc.) with the aid of 3D modeling.
Daily management	-	BIM functionalities can be used to provide information on what has been done on a daily basis, and this information can be input in the model to optimise daily meetings.

Conclusion

Lean implementations depend on people understanding lean principles and why and how they can apply lean to their environment and business needs, deploying it on an operational basis. The appropriate use of BIM functionalities to support lean practices is an important facilitator of successful lean transformations.

To systematically understand what has already been done and potential opportunities, a set of lean practices and BIM functionalities was used for a cross-check of the coverage of applications.

Below, we summarise the main conclusions in three blocks: bibliometric analysis, the degree of application of BIM to support lean practices and gaps and opportunities.

The **bibliometric analysis** showed that:

(a) the number of papers on the subject has grown in the last ten years, probably as a tendency due to the increased use of BIM (Figure 2);

(b) the synergies between BIM and lean practices in the construction phase are reported in publications with diverse focuses, such as lean, management and technology, showing the cross interest in different research forums (Table 3); e

(c) the reported cases mainly involve building projects, with scarce research on the synergies between lean and BIM in infrastructure projects (Figure 3).

A classification of the **degree of application** of BIM functionalities to specific lean practices emerged: practices that have been extensively explored, reasonably explored, and just preliminarily explored (Table 5):

(a) just one lean practice (the last planner system) has been extensively explored;

(b) three have been reasonably explored (the line of balance, Andon and Kanban);

(c) five have just been preliminarily explored (VSM poka-yoke, small batches, and Kaizen events); and

(d) five have not been explored (production cells, standardised work, Heijunka, and daily management).

From this classification, the main aspects already addressed, as well as the **main gaps and opportunities** were identified for further research (Table 7):

(a) the results show that although applications exist, BIM is still underused to support lean, and as a result, fundamental lean practices that could possibly provide support currently remain underexplored;

(b) even for practices that have been extensively explored and reasonably explored, several applications of BIM functionalities were identified that could be further explored, as presented in Table 7;

(c) major opportunities that, to date, have not been explored are related to the use of BIM functionalities to support applications of lean practices in the gemba (the real place where things are done). This can be seen in Table 7, where not explored lean practices typically focus on the field, such as production cells, standardised work, Heijunka 5S, and daily management. Training and communication to spread the use of lean tools to the workforce facilitated by BIM is also a less explored opportunity;

(d) taking management construction activities, i.e., planning, logistics, execution and control, as a reference for an analysis with a closer connection to practical use, the research pointed out that planning is the activity with the most coverage (e.g., the last planner system and line of balance), followed by logistics (e.g., Kanban and small batches), with major opportunities in execution (gemba, as mentioned above) and control (e.g., daily management) (Table 7); and

(e) auxiliary technologies are opportunities for combined use with BIM, enhancing lean practice applications. Mobile computing is mentioned in several selected papers, but with regard to other technologies (such as the IoT, RFID, virtual reality, augmented reality), there is scarce research on the specific use of lean practices for support (Table 6).

The research identified extensive opportunities for BIM functionalities to support fundamental lean practices that currently have no support or scarce support. This is a massive challenge for practitioners and researchers, mainly because both lean and BIM are concepts that still depend on cultural changes in the construction industry for their extended use.

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