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Review

Toward BIM and LPS Data Integration for Lean Site Project Management: A State-of-the-Art Review and Recommendations

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Abstract: Over recent years, the independent adoption of lean construction and building information modeling (BIM) has shown improvements in construction industry efficiency. Because these approaches have overlapping concepts, it is thought that their synergistic adoption can bring many more benefits. Today, implementing the lean–BIM theoretical framework is still challenging for many companies. This paper conducts a comprehensive review with the intent to identify prevailing interconnected lean and BIM areas. To this end, 77 papers published in AEC journals and conferences over the last decade were reviewed. The proposed weighting matrix showed the most promising interactions, namely those related to 4D BIM-based visualization of construction schedules produced and updated by last planners. The authors also show evidence of the lack of a sufficiently integrated BIM–Last Planner System® framework and technologies. Thus, we propose a new theoretical framework considering all BIM and LPS interactions. In our model, we suggest automating the generation of phase schedule using joint BIM data and a work breakdown structure database. Thereafter, the lookahead planning and weekly work plan is supported by a field application that must be able to exchange data with the enterprise resource planning system, document management systems, and report progress to the BIM model.

Keywords: BIM; Lean; IT; LPS; Scheduling; progress monitoring; automation

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1. Introduction

1.1. Research Topic and Scope

The lag of construction productivity behind manufacturing is a well-known fact. McKinsey research shows this discrepancy through an annual growth of 1% for the building industry while manufacturing scored 3.6% during the last decade [1]. Manufacturing success has been realized by a new production philosophy considering both conversion and flow activities. In construction, the conventional thinking of production based only on value-adding processes is still prominent [2]. For instance, material handling and inspection operations are not generally depicted in the critical path model or other activity-based planning methodologies. The term "activity-based" best describes those planning approaches because the project is split into discrete packages of work. The planning network is then built by a logical linking of those activities. As the predecessor and successor relationships are respected, all crews can move freely within the building areas [3]. Therefore, this paradigm promotes an organization in silos and thus emphasizes the proliferation of site coactivity, safety risks, waiting, and other types of wasteful activities, which can reach 49.6% of construction operative time [4]. Neglecting the flow aspect in construction planning impedes the reduction and elimination of less value-adding activities through which the transformation processes are bound together.

Moreover, technology scarcity reduces labor productivity growth in construction [5]. The sector comes second to last in the United States and last in Europe in regard to its Digitization Index [6]. There is rising awareness of the merits of digital technologies, starting with the adoption of two-dimensional tools in the form of computer aided design (CAD) software, which have progressively been replaced by three-dimensional technologies through BIM. This latest was defined in the ISO 29481-1:2016 standard as the use of a shared intelligent 3D object-oriented model of a building to facilitate design, construction, and operations processes [7]. BIM is one of the most robust components of virtual design construction (VDC). Whereas BIM focuses on developing product plans virtually, VDC endeavors to integrate design with construction by incorporating elements of product, process, and organization [8]. The platform of IT tools that BIM offers is used to design virtual models describing the physical and functional characteristics of a building. The intent is to offer a basis for collaborative design, allowing cross-disciplinary sharing of ideas and design adjustments, as opposed to creating rigid and singular design outcomes. Nevertheless, BIM implementation attempts are still restrained to the feasibility and design phases of a building project. At the feasibility stage, it focuses mainly on carrying out preliminary estimates in order to assess the possible cost of construction. At the design phase, it is used to plan and control cost alongside the design in line with the client's budget. This means that less attention is given to digitalizing the construction, operation, and decommissioning phases of a building through conflict analysis, 3D/4D coordination, maintenance scheduling, and so forth. Accordingly, construction professionals need to consider digitalization of all building stages as the norm, fully implement it in all facets, and perceive its benefits [9]. For instance, the digital transformation of construction processes can improve document quality, increase work pace and response time, and alleviate harsh work conditions.

The aforementioned flow ideology and aims make up the essence of the Toyota Production System, which was translated into lean philosophy in 1980 by MIT. The universalization of the lean approach beyond the automobile field allows its application in construction. Hence, lean construction principles emerged from the collaboration of three researchers, Koskela, Howell, and Ballard. In 1993, their knowledge contributions were shared during the first lean construction conference in Finland. Since then, the concept has evolved continuously and has been cultivated by a growing community of researchers within the International Group of Lean Construction [10]. Last Planner System® (LPS), building information modeling, and visual management are the major lean construction practices [11]. LPS was labeled as the first lean construction tool in 1992, as opposed to BIM technology, which developed independently from 1970 in the construction domain long before the introduction of lean philosophy. However, the assessment of professionals' perception of BIM and project results led to BIM being viewed as a waste reduction tool. Thus, it is safe to call BIM a lean tool [12]. In addition, it has been commonly agreed that BIM could enhance some lean construction techniques [13]. Sacks et al. illustrated overlaps between lean principles and BIM functionalities through a matrix with 56 interactions. The grid reveals empirical evidence from practice or research studies of the interrelationship of the two concepts. The sheer number of positive lean and BIM interactions identified supports the argument for their significant complementarity [14]. Later, Ouskouie et al. expanded the existing matrix by adding uncovered interactions related to the operation and maintenance stage of a facility [15].

While adopting the theoretical framework of lean–BIM synergies is still in the early stages for most companies, there is a need to understand the current state of combined lean–BIM implementation patterns during the execution phase of a building through the following steps:

- Identify the prevalent lean and BIM interactions that have been investigated and experimented on by researchers and industrial professionals;
- Find the limitations of the identified strong lean and BIM interconnections;

- Discover the latest research orientations that overcome the current gaps in applying the strong lean and BIM interactions;
- Suggest an integrated information technology system that allows effective application of the prevalent lean and BIM interactions.

The main objective of this study is to address these research issues by conducting a comprehensive review of overlapping lean techniques and BIM functionalities and identifying prevailing lean and BIM interactions that have been explored by academic and industrial communities, examining their implementation flaws, and showing current research directions aiming to bridge the gaps.

The paper is structured as follows: Section 1 introduces the research topic and scope and gives an overview of the major lean construction techniques and the main features of BIM. Section 2 explains the research methodology. Section 3 shows the trends of mutual lean and BIM application and analyzes in detail current research directions toward scheduling and control automation. Section 4 provides a final discussion on the findings and their potential meaning for practice in the area of BIM and LPS integration. Section 5 concludes this study.

1.2. Lean Construction Overview

As mentioned earlier, the expression "lean construction" was coined in 1993 at the first International Group of Lean Construction conference. Since then, researchers have tried to put communicable meaning into the definition of the term in order to deal with the confusion regarding this concept. Mossman presented a chronological history of the definition of lean construction to elucidate this ongoing debate. By analyzing 68 definitions of lean construction, he proposed a table summarizing the most frequently mentioned concepts. By underlining the fact that the lean concept was developed and applied successfully in numerous contexts, he also raised the question of whether we need a lean construction theory [16]. Tzortzopoulos et al. asserted that a lean construction theory was badly needed in order to create new interfaces with other disciplines, such as organizational behavior and economics [17]. Accordingly, we propose the following formalization of the meaning of lean construction obtained from a compilation of various definitions: Lean construction is a production management philosophy for delivering optimal construction projects. Its overarching aims are value maximization and waste reduction. The desired outcomes are reached through a systematic, synergistic, and continuously improved design and building processes and flows.

It is important to note that lean construction is equated with lean project delivery in the Project Production Systems Laboratory (P2SL) glossary [18]. It designates the application of lean thinking to designing and carrying out projects through five interconnecting phases. Those phases were mapped by Ballard in 2000 and symbolize the conceptual representation of the Lean Project Delivery System (LPDS). Each phase contains three modules describing project stages [19]. LPDS suggests various tools and techniques that can be employed either at a specific project stage or throughout the whole project lifecycle. The chapter on lean construction tools and techniques in the Design and Construction book covers LPDS methods by phase, including the following:

- Lean production management: This runs from the beginning of a project to the handover of a facility. It consists of work structuring (WS) and production control. Introduced by Ballard in 1999, work structuring is used before the construction stage to break down products and processes into work chunks in order to dimension production units and organize handoffs between groups [20]. WS deliverables encompass project execution strategies and organizational structures, operations design, and master and phase schedules. From a lean mindset, master schedules should only include special clients' milestones. Phase or pull schedules are best produced by last planners, who can create a reliable network of executable tasks and use float to buffer uncertain activities [21]. Contrary to traditional project management wisdom, we notice that lean construction suggests hierarchical, collaborative, and progressively detailed planning. In order to support continuous workflow, location-based scheduling techniques such as line of balance, flowline and takt-time planning are preferred over the well-known activity-based critical path method (CPM) and program evaluation and review technique (PERT). Planning is followed by control to ensure that project objectives are met. For a lean community, production control means ensuring events conform to the plan. This conceptualization is distinct from traditional project control, where discrepancies in project progress trigger corrective actions. The functions of the Last Planner production control system help to achieve those ends, which also evolved over time. Its first production unit control component, driven by a quality checklist of weekly work, focuses on solving the mismatch between what a superintendent said he would do and what he did. This primary item improves labor productivity and commitment quality, and this key performance metric was labeled percent plan completed (PPC). The PPC could hit 100% if tasks are made ready before their execution date. This is the function of workflow control or a lookahead plan, the second fundamental component of LPS. During lookahead scheduling, last planners divide phase schedule activities into assignments and analyze their constraints before adding those tasks to the lookahead window and thus to the weekly work agenda [22].

- Lean design: This aims to integrate process and product design in the pursuit of TFV goals. It encourages the exploration of alternatives between cross-functional teams rather than handing off single point solutions to downstream disciplines. This strategy fits well-integrated forms of contracts like IPD or design-build projects.
- Lean supply: The objective is to optimize the flow of goods and services, information, and funds between customers and suppliers. The best practices advocated are standardization, off-site fabrication and preassembly, consolidation of transport orders, and long-term supplier relationships.
- Lean assembly: The goal is to minimize in situ installation effort by using several tools, such as just-in-time delivery, one-touch handling, first run studies, multi-skilling, total quality management, and so forth.

The Lean Project Delivery System (LPDS) has proven to be a worthwhile improvement method. The approach relies on collaboration and helps develop a common culture of waste removal from products and processes among all project stakeholders, including owners, designers, builders, and suppliers, at a very early stage of the project. Despite those benefits, the construction industry is still struggling to effectively implement the LPDS, especially to improve visualization and share a reliable flow of information, which are the main capabilities offered by BIM [8]. The technical barriers to LPDS implementation are emphasized by a resistance to change and a lack of standards, regulations, and government involvement [23].

1.3. BIM Overview

The basic concept of BIM related to object parametric modeling was introduced in 1970 by Charles M. Eastman in many industries. As a solution to construction project inefficiency, AEC gradually adopted BIM in the mid-2000s [24]. The National Institute of Building Science defines BIM as a central information management hub of the physical and functional characteristics of a facility. There is no specific commonly accepted description of what BIM stands for: building information modeling, which helps represent and share digital models of construction, or building information management, which addresses the process of managing the information of a structure throughout its lifecycle [25]. Volks et al. expanded the definition of BIM to include its functional, informational, technical, organizational, and legal issues. Functional issues are the first feature of BIM. This feature is inherent to BIM dimensions used for modeling (3D), planning (4D), costing (5D), sustainability (6D), facility management (7D), and safety (8D) [26]. Table 1 summarizes various applications of BIM dimensions.

Table 1. Main applications of BIM dimensions and functionalities.

3D	Visualization, navigation and sharing models
	Drawing and document production
	Clash detection
	Defect detection and control
	Simulation, analysis and optimization of physical and functional performances
4D	Visualization and animation of construction schedules
	Time-space conflict analysis
	Automated generation of tasks
	Optimization of construction sequences
	Progress tracking
	Procurement tracking (Supplier integration)
	Manage site logistics (laydown areas and site layout, access to site, location of equiments and resources)
5D	Quantity takeoff
	Cost estimating
6D	Carbon footprinting
7D	Performance monitoring
	Asset tracking for maintenance operations
8D	OHS rules checking
	Safety hazards identification (prevention of falling . . .)
	Safety training and emergency management

The transition from traditional 2D representation to 3D object-oriented modeling reveals the low maturity level of an organization in BIM implementation. At level 1 BIM maturity, collaboration is often limited to an ad hoc exchange of models using export and import functions. The second level of BIM maturity is associated with advanced modeling, where the 3D object parameters are upgraded at each project phase to support an exchange requirement. In this way, we add additional dimensions such as time (4D) or financial resources (5D) while maintaining separate BIM processes. The third and highest level of BIM maturity supports the idea of an integrated object-oriented model, shared and nurtured by project actors in the cloud. From this vision, the generated model is unique and encompasses all of the project's dimensions and disciplines [27].

Researchers advocate that the use of BIM functionalities supports LPDS phases. For instance, integrating BIM with supply chain partner databases is a powerful opportunity for pulling information on the delivery of materials and product design from the supplier. In addition, automatic quantity take-off from the BIM model is more accurate and minimizes human counting errors [8].

Those n-dimensional models are extensions of the 3D BIM model. They are provided by expert applications that add multiple types of design information required by various stakeholders at each phase of the building lifecycle (Figure 1). The transformed dataset is either attached to the central information repository of BIM or reported separately [28]. The second feature of BIM related to informational issues deals with providing a suitable informational structure and allowing a successful data exchange between software. Thus, buildingSMART designed the Industry Foundation Classes (IFC) as a response to the data interoperability needs of the AEC industry. They use an object-based file format with a data model that organizes data elements and standardizes the way they are linked together. Since then, it has been widely believed that the IFC schema can help to meet the needs of all AEC practitioners until we recognize the importance of information model views in supporting specific task and workflow requirements. Thus, Information

Delivery Manual frameworks and Model View Definitions were developed as a response to task-related data exchanges (Figure 1). The former maps business processes and specify information exchange requirements of involved actors at a particular stage of a project, and the latter encapsulates several exchange requirements to support expert application functionalities [29].

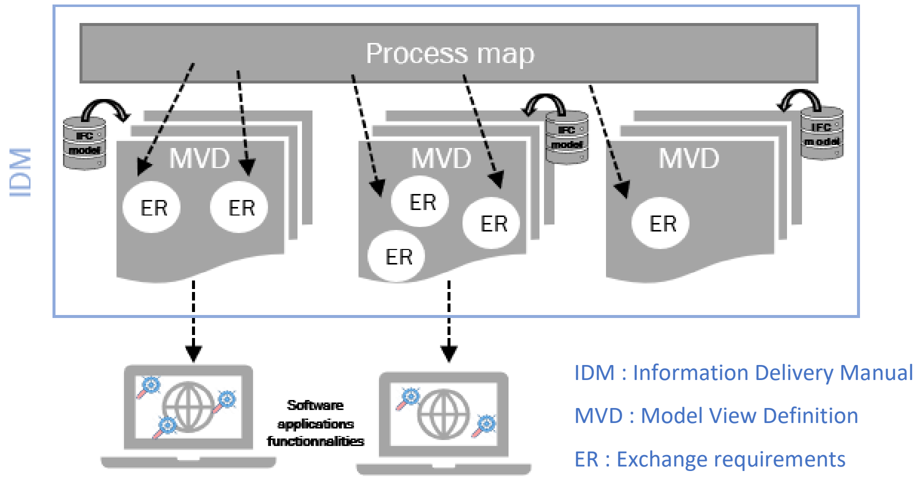


Figure 1. Description of IDM framework and its relation to BIM functional issues.

Functional and informational requirements determine the technical characteristics of the building model by defining its level of detail (LoD) and consequently the model creation process. The five main levels of LoD (100, 200, 300, 400, 500) were established in 2008 by the American Institute of Architects. They quantify the minimum information required in the 3D model to assist a certain usage at a given project stage [30]. The 3D model is then created from scratch for a new building or through a point-to-BIM process for an existing building with little or no documentation. Finally, organizational and legal issues concentrate on fostering partner collaboration, preserving model ownership, and aligning academic content with industry advances in this area.

2. Methodology

To ensure a comprehensive review of the impact of information technology on prevalent synergistic lean BIM applications, we need to gain a deep understanding of lean and BIM complementarity. Thus, the following steps were taken: (i) set search keywords and string; (ii) conduct paper search in Scopus and Web of Science databases; (iii) eliminate duplicate publications; (iv) collect inventory of lean techniques and BIM functional issues highlighted in each manuscript; (v) conduct in-depth exploration of benefits and flaws of highly adopted lean and BIM correlations; and (vi) examine the ability of information technology to boost the materialization of lean principles through BIM capacities. The Figure 2 present the research methodology that we'll explain bellow.

In the first step, we conduct a three-level advanced search. First, we combined general keywords "lean", "BIM", "building information modeling", "IT", "information technology", "site", and "execution" with operators AND and OR to identify prominent collision areas of lean techniques and BIM capabilities. The second search level included keywords "BIM", "building information modeling", "planning", "scheduling", "generation", "automation", and "automatic". The third and final search iteration covered keywords "BIM", "building information modeling", "automation", "automatic", "progress tracking", "progress monitoring", "activity progress", "progress". The research scope was limited to construction operations and excluded design, maintenance, and demolition stages of a building. We ran the syntax in principal search systems to acquire high-quality and up-to-date papers. The first query output was 56 and 19 papers, respectively, found in Scopus and Web of Science. As the number of publications related to this research subject is limited, all published documents from 2010 to 2020 were reviewed. After eliminating duplicate references, only 65 papers remained. As shown in Table 2, conference papers represent 65% of the total documents in our sample, followed by articles, representing 32% of papers and 3% of reviews.

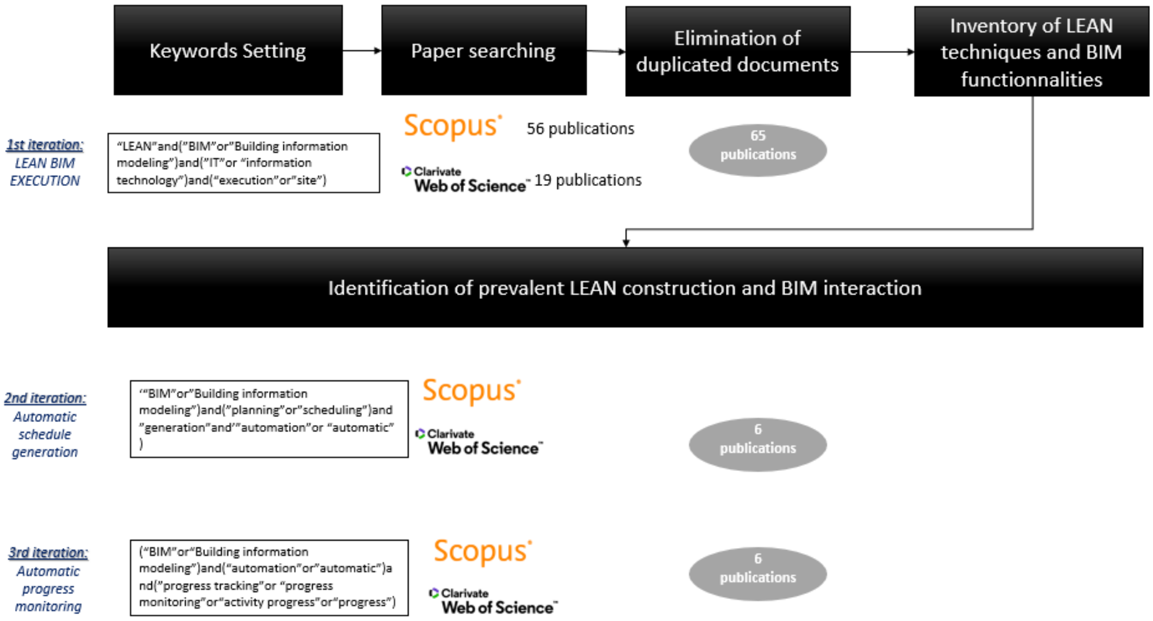
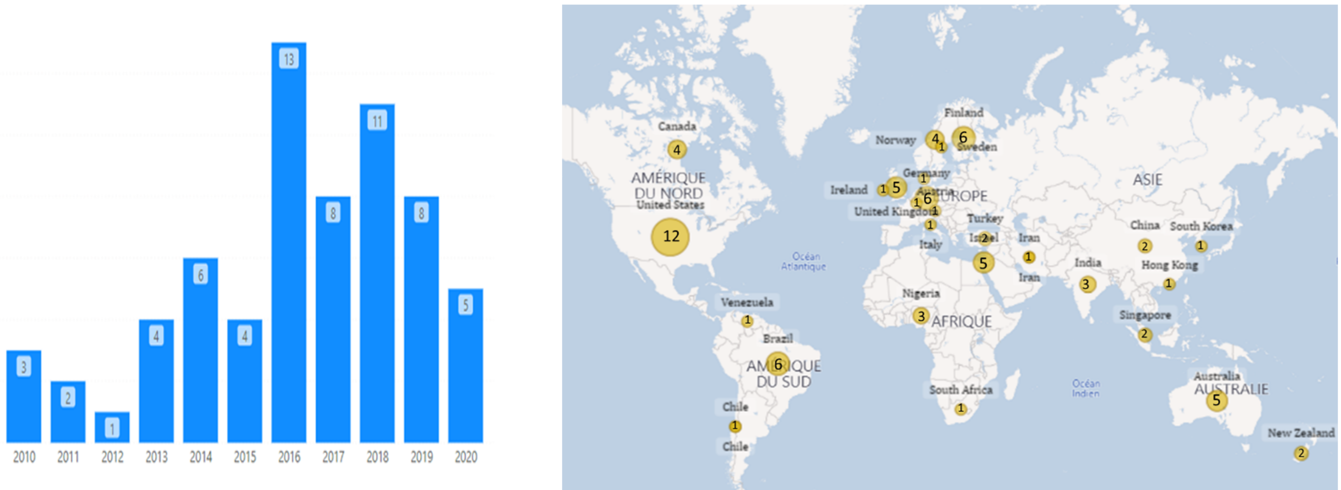


Figure 2. Research methodology.

Publications related to the interaction between lean and BIM enhanced by information technology at the execution stage were rare before 2013. The main countries with lean and BIM synergy were Israel, Finland, and the United States (Figure 3). A peak of 13 research contributions was observed in 2016. Since then, every year 8 papers have been published on average all over the globe.



(**a**) (**b**)

Figure 3. Distribution of number of publications addressing lean–BIM interaction at execution stage (**a**) per year and (**b**) per country from 2010 to 2020.

Table 2. Reviewed publication types.

Publication Type	Publication Number
Conference papers	**42**
International Group for Lean Construction	28
Annual Association of Researchers in Construction Management Conference	3
IOP Conference Series	2
Communications in Computer and Information Science	1
Computing in Civil and Building Engineering	1
Construction Research Congress	1
CSCE General Conference	1
International Conference on Computing, Networking, and Informatics	1
International Conference on Engineering, Technology, and Innovation	1
International Symposium on Automation and Robotics in Construction	1
Lecture Notes in Computer Science	1
Procedia Engineering	1
Articles	**21**
Automation in Construction	4
Engineering, Construction and Architectural Management	3
Journal of Construction Engineering and Management	2
Civil Engineering Journal (Stavebni obzor)	1
Construction Innovation	1
Construction Management and Economics	1
Electrical Construction and Maintenance	1
Frontiers of Engineering Management	1
Journal of Engineering Design and Technology	1
Journal of Information Technology in Construction	1
Journal of Management in Engineering	1
Lean Construction Journal	1
Science and Technology for the Built Environment	1
Sustainability	1
Reviews	**2**
Engineering, Construction and Architectural Management	1
International Journal of Mechanical Engineering and Technology	1
Total	**65**

A deep analysis of these publications allowed the authors to complete a grid to show the adoption frequency of both lean construction techniques and BIM functionalities mentioned in Section 1. In the next section, we present our quantitative lean and BIM interaction matrix results based on the first iteration of advanced publication search. The second and third iteration outputs were employed for analyzing mainstream automation efforts in scheduling and control, presented in Section 3. Six journal articles were in each research area were deeply studied for automatic schedule generation and automatic progress monitoring.

3. In-Depth Analysis and Results

In this phase, we conducted a content analysis of the literature sample to obtain insights into current trends and patterns in the implementation of lean construction and

BIM. The papers' key messages were sorted to provide the reader with a comprehensive summary of their main focus through a weighting matrix (Section 3.1), the background of lean IT tools supporting production scheduling and control (Section 3.2), and current research aiming to automate production planning and control (Section 3.3).

3.1. Weighting Matrix of Lean Construction and BIM Interactions

The matrix proposed is called a weighting matrix because it provides a measure of adoption frequency for all items that compose. Its vertical axis represents lean construction techniques presented in Section 2 and its horizontal axis represents BIM functional issues related to each dimension as identified in Section 3. Figure 4 summarizes the recurrence of lean and BIM interconnections in the studied papers. Only significant interactions are represented in Figure 4; BIM functionalities and lean construction techniques with fewer than five interactions were removed from the matrix. At the construction stage of a building, the top lean construction concepts employed in a pilot project or through virtual simulation are those related to the lean production management module of LPDS. Specifically, we refer to work structuring and production control techniques, which rely on LBS and LPS, as detailed above. On the other hand, the visualization of construction schedules, sharing and navigating across the 3D building model, and work progress tracking constitute BIM capability summits recently investigated. Leveraging the visualization power of BIM to support collaborative production scheduling and control is major evidence that BIM contributes indirectly to lean goals. It allows virtual Gemba walks, which let workers get a better understanding of what the final building is going to be and what activities are planned for a selected period. Moreover, the visualization feature of BIM facilitates face-to-face collaboration between multidisciplinary trades, increases information availability, and enables first run studies. All of these pros support the decision making for the best performing and optimized work methods and sequences [31]. Likewise, lean construction launches collaborative, predictable, and steady rituals that ease the introduction and effective implementation of BIM-based technologies [32].

3.2. Lean IT Tools Supporting Production Scheduling and Control

Based on the lean construction and BIM interactions weighting matrix shown in Figure 4, it mostly comprises BIM-LPS co-application during construction execution. Actually, the area of BIM-based production management systems during the execution phase was relatively under-researched before 1999. Most studies focused only on 3D model visualization at the pre-construction and design stages. Even existing BIM construction management tools such as Autodesk Navisworks, Tekla BIMsight, and Solibri remain limited in terms of detailed production planning, scheduling, and control. Most of them offer 4D planning capability only at the master schedule level. From 1999, Workplan software, developed by Cho et al., was among the few notable systems that first supported LPS methodology. The database program guides crew foremen on how to define work packages, check constraints, allocate resources, and release weekly work plans as well as report field progress and reasons for plan failures [33]. However, the Workplan system has missing features, for instance work package breakdown with task and constraint level assignments, BIM model visualization, and an intuitive and ergonomic interface, which impede laborers' engagement [34].

BIM capabilities / Lean techniques	Automated generation of tasks	Clash detection	Cost Estimating	Defect detection and control	Drawing and document production	Manage site logistics	OHS rules checking	Optimization of construction sequences	Procurement tracking	Progress tracking	Quantity takeoff	Safety hazards identification	Safety training and emergency management	Time-space conflict analysis	Visualization of construction schedules	Visualization, navigation and sharing models	Total
Work structuring (MS, PS, LBS)	2	6	3	3	2	6	1	3	5	18	8	3	1	9	17	13	**100**
Production control	2	6	3	3	2	6	2	2	7	17	7	3	1	7	17	12	**97**
Total quality management	1	7	2	6	2	4	4	1	1	6	6	4	2	3	7	7	**63**
Just-in-time deliveries	2	2		2		9	3	1	9	6	4	3	2	2	8	4	**57**
Big rooms		6	2	7	3					6	6			2	7	10	**49**
Precast		3	1	2	2	4	1		4	6	5	1	1	2	7	4	**43**
First run studies	1	1		2	1	2	2	1	1	2	1	2	1	1	4	2	**24**
Exploration of alternatives	1	2	1	2	1					1	3				4	4	**19**
Improved work conditions	1	1		1	1	2	2	1	1	1	1	2	1	1	2	1	**19**
Set integrated contracts (IPD)	1	2		1		1	1			2	1	1	1		2	3	**16**
Takt time planning	1	1		1		1	1	2	1	1	1	1	1	2	1	1	**16**
Multi-skilling	1	1		1		1	1	1	1	1	1	1	1	1	1	1	**14**
Standardization		1		1		2			1	1	2				2	2	**12**
Line Balancing (Heijunka)		1	1		1	1	1			1	1	1		1	1	1	**11**
Preassembly (Kitting)				1		1			1						2	2	**7**
Transport orders consolidation						2			1	1					2	1	**7**
Total	**13**	**40**	**13**	**33**	**15**	**42**	**19**	**12**	**33**	**70**	**47**	**22**	**12**	**31**	**84**	**68**	**554**

Figure 4. Lean construction and BIM interactions weighting matrix.

Later, in 2003, Chua et al. [35] introduced the integrated production scheduler to reduce lookahead planning uncertainties. The proposed model handled resource and information constraints in addition to process prerequisites. Each constraint item had an estimated availability time (EAT) attribute that was pulled from respective project suppliers. By applying the theory of constraint (TOC) and buffer management, IPS could determine an activity category in the lookahead plan according to its constraint's status [35]. Nevertheless, the IPS tool did not involve last planners or the 3D product model. In the meantime, Spriprasert and Dawood [36] suggested a multi-constraint planning technique, the lean enterprise Web-based information system (LEWIS). This decision support system integrates product and process models with upstream and downstream information in a central SQL database. Its interactive browser makes lookahead analysis accessible. It also allows last planners to add sub-tasks under constraint-free activities. Moreover, predecessors and successors of each selected task can be visualized throughout a 3D AutoCAD environment, and a GSM/GPRS network is used to send work instructions to labor mobiles. Nevertheless, the authors acknowledge that future development of LEWIS should tackle the interoperability issue with heterogeneous applications and databases. Apart from integrating LEWIS and SEEK, the platform should become more user-friendly [36].

Later, in 2006, the Center of Integrated Facility Engineering came up with a new approach called virtual design and construction (VDC). VDC was defined as "the use of multidisciplinary design and construction models including product, work processes and team's organization in order to support business objectives" [19]. Eastman et al. explained that VDC is the practice of using BIM to virtually test product and construction processes to examine the overall project performance before executing work in the field [37]. VDC can also employ other tools beyond building models to enable, for example, site delivery simulation. VDC techniques support LPDS modules such as early involvement of downstream stakeholders through a 4D product–process–organizational modeling technique.

ConstructSim is another construction simulation system, developed by Bentley, in which a list of constraints is predefined. It enables planners and technical managers to track constraint status, visualize product and process status, and create animations of construction schedules. In 2009, Sacks et al. noted that controlling work in progress can help achieve a smooth and stable flow in production processes. Accordingly, they initiated an online 3D status board displaying past, present, and future work with traffic light signals and icons [38]. Following the CONWIP research, Sacks et al. developed a BIM-based workflow information system supporting LPS that they called KanBIM. Their prototype facilitates short-term planning and monitoring and provides a clear visualization of task maturity, including planned activities and those under way [39,40].

In 2013, an analogous research idea emerged, which Dave called VisiLean. At that time, the concepts KanBIM and VisiLean influenced and complemented each other. VisiLean, a software as a service, deals with developing production schedules, whereas KanBIM focuses on monitoring daily production progress. Today, VisiLean is a commercial cloud solution that supports multiple planning levels and resolutions such as phase, lookahead, and weekly planning. In addition, a mobile app pushes task information to workers, including attached files and imported quantities. The workers are invited to make tasks and report work package status. As VisiLean is directly integrated with BIM, task progress is visualized through model views. However, a number of shortcomings make VisiLean incomplete; for instance, the automatic creation of tasks from predefined BIM information and the inclusion of costs and quantities from the BIM model are lacking [34,41]. Nowadays, last planner workflow control software vendors are numerous, including Ourplan, developed by DPR Construction and rebranded recently as BIM 360 Plan by Autodesk. vPlanner from Ghafari Associates is another IT support compatible with LPS [17]. Figure 5 summarizes the main IT software supporting production scheduling and control components as stipulated by Ballard in the current LPS process benchmark [42].

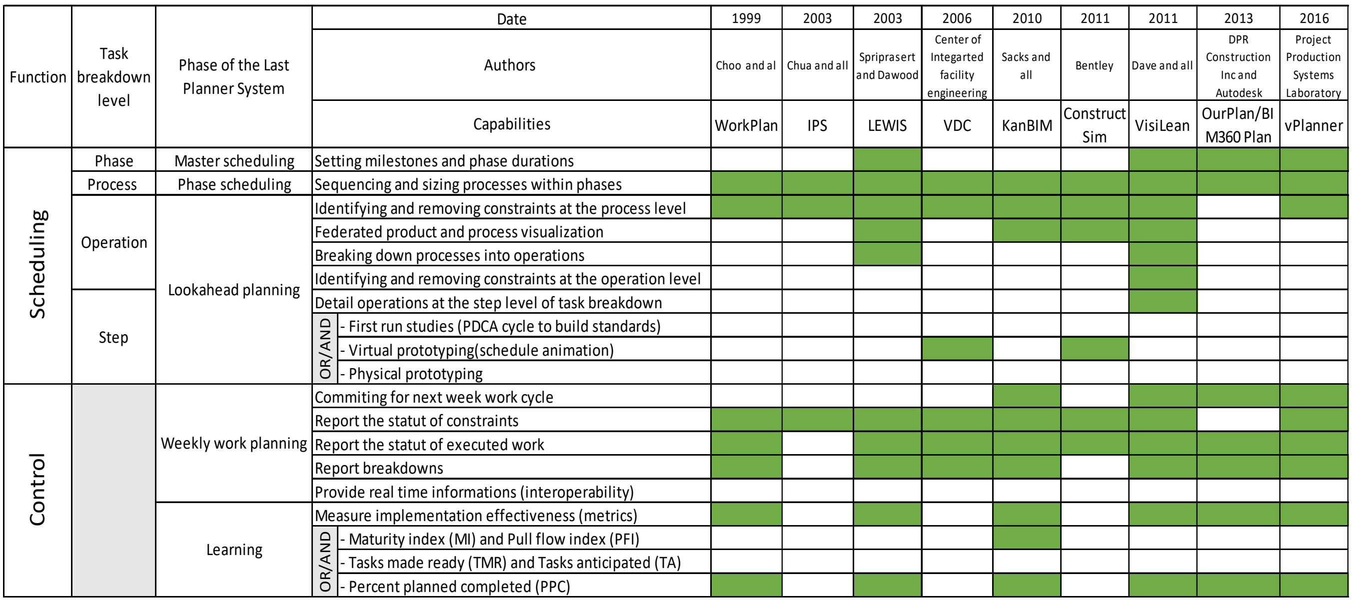


Figure 5. Capabilities of IT software supporting LPS.

In sum, Figure 5 demonstrates the completeness of the VisiLean software system compared to its rivals in terms of production scheduling and control functionalities. Indeed, it enables users to enter phase milestones and plan process sequences; allows process breakdown into operations and steps with associated product and process visualization; permits constraint analysis at the process, operation, and step levels; makes negotiation of weekly work plans possible; and secures commitments, collects and reports constraints and task status according to workers' observations. Despite the reported advancements pertaining to VisiLean, the system does not yet use the full potential of BIM. Actually, the rich building information embedded in BIM needs to be fully utilized to facilitate automatic generation of project schedules. In addition, automation challenges should cover project progression data collection methods.

3.3. Research Orientations in the Field of Construction Planning and Control Automation

Automation of production planning and control has garnered much attention from researchers and construction practitioners in recent years. It is considered as a pathway to solve traditional key construction concerns, specifically their reliance on manual processes for schedule execution and progress monitoring. In fact, ongoing processes are extremely laborious, very time-consuming, and too infrequent to allow for prompt decision making. Those tedious tasks could benefit from advances in information technology. From the ISACA point of view, information technology represents "all facilities used to input, store, process, transmit and output data in different forms" [43]. The following subsections describe how researchers leverage information technology to automate schedule generation (Section 3.3.1) and progress tracking (Section 3.3.2).

3.3.1. Automated Trial Runs for Scheduling

Exploiting information stored in 3D models to assist in generating schedules, including activities logic and times, can boost scheduling efficiency and relevance.

BIM-based scheduling has been addressed in previous research efforts. In 2007, De Vries and Harink presented an algorithm that derives vertical and horizontal relationships between building components of a 3D CAD model. Depending on the component type, a construction analysis module reads appropriate equipment, labor, and formulas to calculate activity duration from an external database. A log file registers the building component's name, type, duration, and adjacent neighbors, which enables a planning schema to be generated under the assumption of unlimited resources [44].

Subsequently, Kataoka described a new system to generate multiple scenario schedules with related resource quantities based on early-stage design models and construction method knowledge templates. Each construction method template defines the conditions and rules to be applied for decomposing a primitive geometry into components, defining attributes and component set-related activities as well as task predecessors and successors. The ability for users to change construction methods makes what-if simulations possible within the structural planning using an interpretable template system (SPLIT) [45]. In the same year (2008), Ibrahim et al. proposed a conceptual model to automate the formulation of work breakdown structure (WBS). "Elements", "work section", "construction aid", and "physical location" were identified as the most frequently used decomposition criteria for work package generation. Effectively, the implementation prototype produces realistic groupings of components for almost all criteria except "construction aid" because related attributes are often absent in a 3D building model [46].

Later, in 2013, Kim et al. established a framework for automating the generation of construction schedules. The proposed system carries out the following steps: first, it extracts BIM element locations, materials, and quantities per work zone; second, it calculates element duration using production rates from the RsMeans database; third, it develops sequencing for the generated activities according to user priorities; fourth, it converts the output into a Microsoft Project format file; and finally, it allows the user to refine the preliminary schedules considering real-world circumstances [47].

In 2015, Liu et al. presented an automated approach for generating optimized component-centric activity-level schedules. In the suggested mock-up, BIM provides rich product information to run process simulation that includes not only quantity take-offs, but, more importantly, building element connections and supporting relationships. Each BIM component is supplemented with work package information related to its type. Work package properties such as activity name, description, duration, and resources are sourced from WBS stored in MS Access tables. By means of predecessor and successor relationships, the work packages are interrelated to form process patterns that are reusable for similar building elements and building projects. Subsequently, the process simulation model uses both BIM topological logic and process pattern flows to perform construction sequencing. The latter module also calculates the objective function, or the project duration, to feed the particle swarm optimization (PSO) algorithm, which in turn searches for an optimum solution by varying the priority for resource values assigned to work packages considering available loaded resources loaded [48].

More recently, Wang and Lin proposed an integrated approach that extends the 3D building information model with a work package information model in order to furnish all required data for the resource constrained project scheduling problem (RCPSP) solving process. The integrated model was established in three main steps: First, the structure and content of work package templates (WPTs) are defined. In addition, BIM element types and material attributes are renamed using classification codes to ensure consistent matching with related work package templates. After BIM and WPT association, work package instances are generated per work area; then, they are grouped by quota combinations that determine usage conditions with related resource items. The authors sourced quota and resource data from a Chinese ontology-learning standard database. To perform work package instance sequencing, precedence relations are defined according to element properties such as location, category, and construction area. The last step is to run a multimode resource constrained scheduling algorithm to find the best sequencing and resource allocations that optimize total project cost and makespan [49].

Current research studies overlook the BIM-based resource constraint scheduling problem. Some integrate optimization methods with BIM and process simulation to study the effects of construction solutions on key project performance indicators. Inspired by system dynamics simulation used for safety management, the operation's prerequisites could be optimized by applying a simulation approach to construction scheduling, which would help deliver products on time [50,51]. In addition, potential improvements of suggested artifacts must be considered, for instance, for capturing weather, workspace, and safety constraints; identifying vital factors that influence project performance by varying model parameters; predicting construction method productivity rates using data mining technologies; and so forth. The next crucial evolution is to keep 4D BIM models updated in real time by conducting automatic progress tracking of construction operations. This feature will be addressed in the following section.

3.3.2. Automation Trial Runs for Progress Monitoring

Methods that streamline the analysis and interpretation of visual data collected on site are major concerns for construction companies and the computer vision and robotics communities.

The assessment of automated processes for work package component progress is divided into the following steps: First, sensing technologies such as RFID tags, laser scanners, and images and videos captured with cameras, unmanned aerial vehicles, or augmented reality are used to acquire data of as-built scenes. Second, relevant information is retrieved to enable reconstruction of the as-built 3D point cloud. Then, a comparison between the as-planned and as-built models is conducted in order to estimate component progress status. Finally, data processing results are displayed.

It is important to mention that the difficulty of interpreting collected information varies depending on the chosen data acquisition method and the construction environment characteristics. This is especially true in the case of indoor environments, which consist of various types of components that are subject to surface changes (paint, insulation, etc.) The challenges of interior scenes are less addressed by current research activities than those of exterior environments [52]. As can be seen from the literature, studies are mainly focused on the static and dynamic occlusion challenges caused by progress itself and by temporary structures [53].

For instance, Ibrahim et al. responded to these issues by selecting an ideal fixed, calibrated, and pre-aligned camera position that offers visibility from various angles [48]. On the other hand, Golparvar et al. used a set of images collected by superintendents from different viewpoints and in different lighting conditions. Using a photogrammetry technique called structure from motion (SfM), they were able to reconstruct sparse as-built 3D representations from unordered and uncalibrated photo collections. A Euclidean registrar superimposes the as-built point cloud with the as-planned BIM model. Subsequently, they used a multi-view stereo (MVS) algorithm to improve reconstruction density before categorizing the models' voxels using a voxel coloring and labeling algorithm. Voxel classification included occupied (O), empty (E), blocked (B), and visible (V) categories [54]. Experts in 3D reconstruction seek completeness and accuracy in generated models. For example, the BIM-assisted SfM procedure together with MVS presented by Karsh et al. in 2014 provides an errorless point cloud compared to other reconstruction approaches using real-world construction data [55,56].

Another application of automated and frequent construction site surveying is the use of camera-mounted unmanned aerial vehicles (UAVs). In practice, this method primarily relies on experienced pilots who drive the drones. Autonomous navigation of UAVs using simultaneous localization and mapping techniques and GPS waypoints has been recently investigated by researchers [53]. In Golparvar et al.'s framework for model-driven acquisition and analytics of visual data using UAV, knowledge of expected changing locations and ideal viewpoints can be provided to the drone by 4D BIM for planning its navigation path [54]. Despite advances in flight planning methods, this field still has unresolved shortcomings, such as the loss of GPS signals in indoor environments and crush risks due to the loss of calibration of magnetometer sensors [53].

In the end, visualization of progress monitoring results is fundamental. A comparison of progress inspection solutions demonstrates that mobile augmented reality tools perform this mission best. Indeed, they can be used in both interior and exterior environments, and they are cheap and require minimum setup and training time. However, current AR software unfortunately has problems with accurate alignment and does not perform data analysis for progress estimation purposes [52].

4. Discussion

Connecting back to the initially stated research questions, we found from the literature review that the Last Planner System® of production planning and control is the most investigated and experimented lean construction technique.

Alongside the growing interest in LPS methodology, the visualization capability of BIM, determined to be independent from MICMAC analysis [57], is are gaining as much attention among researchers and industrial professionals, especially related to construction schedule animation and progress monitoring.

Thus, the authors can state that a synergy between BIM and LPS is the most promising interaction between lean construction and BIM. The area of BIM-LPS co-application was addressed by several studies that mentioned so-called lean IT tools that support some aspects of LPS and allow a link to BIM models for visualization. Nevertheless, none of these tools support LPS to its full extent, as shown in Figure 5. Most support only collaborative phase planning but neglect systematic task breakdown and commitment with last planners, also claimed by Schimanski et al. [58].

The shortcomings of IT implementation with respect to LPS are emphasized by the underdevelopment of BIM linkage capabilities using data integration and processing construction sequencing, quantity take-off, coordination, supply chain management, and so forth. For instance, it emerged from our critical review of lean IT tools that even VisiLean lacks automatic task creation and does not pull cost and quantity information from the BIM model. Accordingly, we can verify Schimanski's statement about the lack of a sufficient conceptual model for BIM and LPS integration in construction execution. Therefore, automating BIM data inclusion with LPS should be inherent in a capable integrated BIM-LPS system.

Over the last decade, researchers have explored BIM-LPS interactions such as automated construction schedule generation, automated cost estimation, and real-time progress monitoring independently. Recently, Schimanski formulated a new theoretical model for true BIM and LPS integration on the data processing level. His proposed Beam! artefact extends Sacks's list of requirements for a BIM-based production management system. Explicitly, it adds a clear definition of roles and automatic quantity take-off from the BIM 3D model for estimating the budgeted cost of work scheduled (BCWS), also called planned value (PV). Generally, the Beam! process digitally follows the LPS steps and allows a manual link to BIM objects via a Beam! board. The digital process Kanban (DPK) and digital operation Kanban (DOK), describing phase processes and operations, are created individually by last planners through the Beam! app. They are then arranged via touch control on the Beam! board by the Beam! king (the general contractor). The setting of DPK duration and estimated cost in addition to planned value distribution over subordinated DOK is also undertaken by last planners [59].

In our view, the integrated BIM-LPS system should not be restrained to automatic quantity take-off for production management. Furthermore, it must consider all BIM and LPS interactions shown in Schimanski's matrix [58]. Notably, BIM data must be used for automatic generation of DPK and DOK and their preliminary arrangement in a pull schedule. As BIM object data will be input for phase plan generation, the links between BIM objects and DPK and DOK will be automatically achieved. An external database storing DPK with respective duration and subordinated DOK information will be absolutely needed. Thus, we propose to complete the generic conceptual model proposed by Schimanski [58] through a detailed mapping of BIM functionality contributions along the LPS process (Figure 3).

In our integrated model presented in Figure 6, project microzoning and objectives will be incorporated in the BIM model at the master schedule level, which will enable customized data retrieval of drawing and quantities. Subsequently, a preliminary phase schedule will be generated automatically using extracted quantities and production rates from a WBS database. Project managers will be able to visualize the processes and operations generated in the schedule with their interrelated BIM objects on a BIM lean planner (BLP) board. After user refinement in BLP, the final phase schedule will be ready and accurate to allow 4D simulation. For each added process, the user must manually specify its duration and associated operations and rates. Following process breakdown of added items, last planners will proceed to the operation's constraint management by selecting a worker from his agency from a catalog, who will execute the task, required materials, tools, and documentation to perform each operation. To make these operations feasible and practical in the construction field, they should be carried out in a BIM lean field app. Specifying the operation's constraints will help to estimate operation cost and thus project cost. To that end, we will need to set up gateways between the task management software and human resources, purchasing, and document management systems. At the end of the lookahead planning process, workable backlogs will be released and communicated online with their inherent information to workers assigned through the BIM lean field app in order to get their commitment. Finally, reporting of operation progress and expenses must be loaded in the central project repository, the IFC model. That will be used for reporting project performance by comparing planned and real progress and cost.

If we succeed in overcoming the interoperability issues related to this integrated BIM-LPS model, we will still need to consider ownerships risks. Questions such as who owns the model, who owns information in the model, and who has access to the model will arise sooner or later. Undeniably, blockchain technology can best handle such data security challenges, guaranteeing a controlled collaborative environment around BIM.

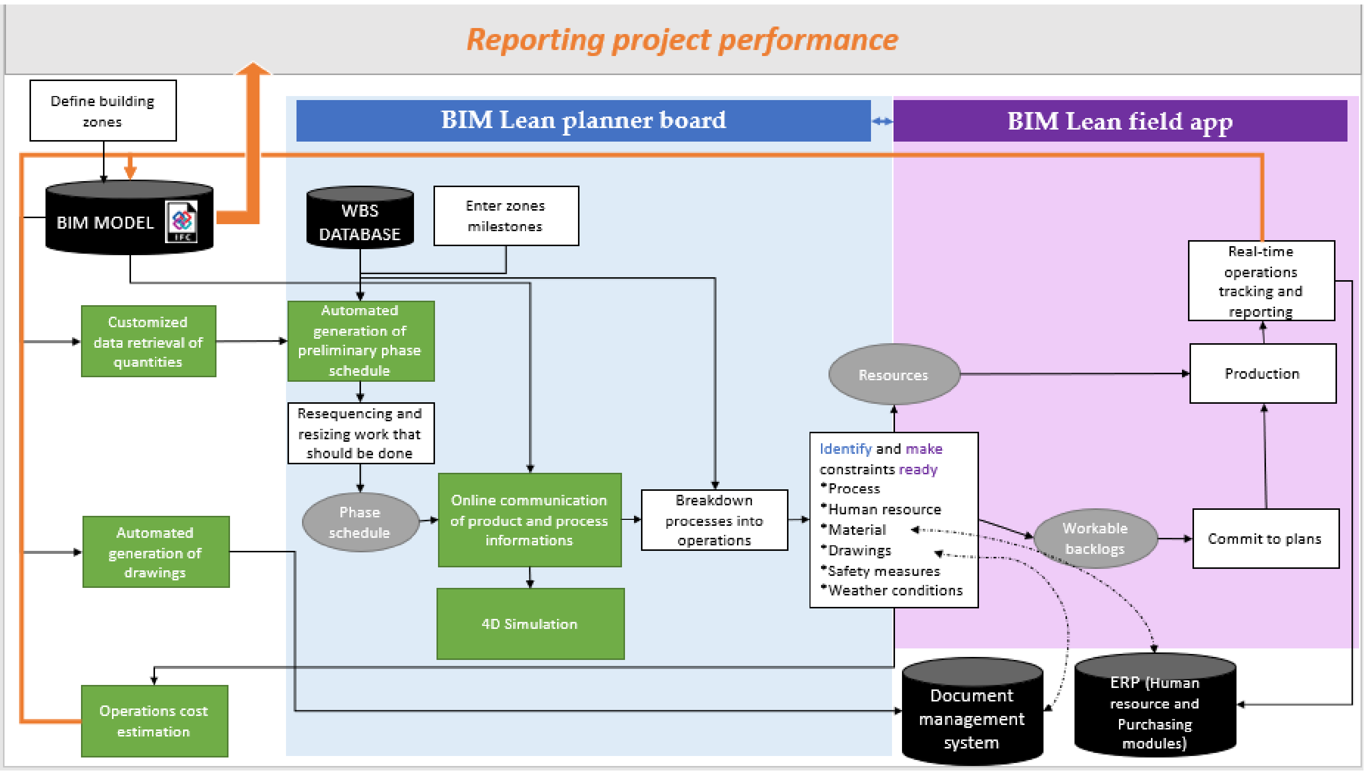


Figure 6. Detailed mapping of BIM functionality contributions along LPS process.

5. Conclusions and Further Works

This paper deals with a state-of-the-art review of recent developments on interconnections between BIM and lean construction at the building execution stage. Altogether, 77 papers published in AEC journals and conferences over the last decade were reviewed. After an in-depth analysis of selected publications, the authors identified prominent interactions between lean construction techniques and building information modeling functional issues. Prominent issues deal with leveraging BIM visualization capabilities to support collaborative planning by last planners and progress tracking of field operations. The authors also show evidence of automation limitations of current BIM-based information technology software supporting the Last Planner System®. Unfortunately, most IT software that assists project managers with effective planning, analyzing constraints, assessing workloads, and controlling site progress still relies on manual processes and does not use BIM data. These limitations impede a true BIM and LPS integration at the data processing level and make current lean IT tools highly laborious, subjective, and error-prone. This statement led us to deeply examine researchers' contributions in the domain of automating construction schedule generation and progress monitoring. We found from the literature that the two automation realms are investigated separately. Thus, we propose to build an integrated BIM-LPS system comprising the two applications. The first web app, BIM Lean PLANNER Board, efficiently matches BIM components and WBS packages with their related resources and production rates to generate automatic phase schedules. The second app, BIM Lean FIELD App, allows site managers to carry out lookahead and weekly work planning. The BIM Lean FIELD App sets out gateways with the human resources, purchasing, and document management systems for constraint analysis. It also enriches the BIM data model with detailed task information and progress, which enables better project performance reporting.

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References

1. Changali, S.; Mohammad, A. The Construction Productivity Imperative. McKinsey & Company, 2015. Available online: https://www.mckinsey.com/business-functions/operations/our-insights/the-construction-productivity-imperative (accessed on 1 May 2021).
2. Koskela, L. Application of the New Philosophy to Construction. CIFE Technical Report. 1992. Available online: https://www.leanconstruction.org/media/docs/Koskela-TR72.pdf (accessed on 1 May 2021).
3. Kenley, R.; Seppanen, O. Location-based management of construction projects: Part of a new typology for project scheduling methodologies. In Proceedings of the 2009 Winter Simulation Conference (WSC), Austin, TX, USA, 13–16 December 2009; IEEE: Piscataway Township, NJ, USA, 2009; pp. 2563–2570.
4. Horman, M.J.; Kenley, R. Quantifying levels of wasted time in construction with meta-Analysis. *J. Constr. Eng. Manag.* **2005**. [CrossRef]
5. Bello, S.A.; Oyedele, L.O. Cloud computing in construction industry: Use cases, benefits and challenges. *Autom. Constr.* **2021**, *122*, 103441. [CrossRef]
6. Zeiss, G. Digitization Could Boost Construction Productivity. Available online: https://geospatial.blogs.com/geospatial/2017/03/digitization-increase-construction-productivity.html#:~:text=Digitization%20could%20boost%20construction%20productivity,-The%20CG%2FLA&text=Just%20about%20every%20speaker%20referred,productivity%20in%20the%20construction%20industry.&text=McKinsey%20Global%20Institute\T1\textquoterights%20Industry%20Digitization,digital%20workers%20in%20each%20sector (accessed on 6 March 2017).
7. Centre des Ressources Technologiques et de L'innovation Pour le Bâtiment, CRTI-B. Guide D'application BIM Luxembourg. 2017. Available online: http://www.digitalbuilding.lu/content/1-guide-application-bim/Guide-BIM-Luxembourg__V1-0.pdf (accessed on 1 May 2021). (In French)
8. Aslam, M.; Gao, Z. Integrated implementation of Virtual Design and Construction (VDC) and lean project delivery system (LPDS). *J. Build. Eng.* **2021**, *39*, 102252. [CrossRef]
9. Aghimien, D.O.; Aigbavboa, C. Digitalization in construction industry: Construction professionals' perspective. In Proceedings of the Fourth Australasia and South-East Asia Structural Engineering and Construction Conference, Brisbane, Australia, 3–5 December 2018.
10. Dupin, P. Fondamentaux du Lean Construction. In *Le Lean Appliqué à la Construction*; Eyrolles: Paris, France, 2016; p. 18. (In French)
11. Castiblanco, F.M.; Castiblanco Jimenez, I.A. Qualitative Analysis of Lean Tools in the Construction Sector in Colombia. In Proceedings of the 27th Annual Conference of the International Group for Lean Construction (IGLC), Dublin, Ireland, 6–7 July 2019.
12. Ningappa, G. *BIM a Lean Tool? Use of Lean and Building Information Modeling in Construction Process; Does BIM Make It Leaner?* Lambert Academic Publishing: Sunnyvale, CA, USA, 2011.
13. Van de Walle, R.; Vandewalle, P. When BIM Becomes a Lean-Tool: Approach for BIM in Process-Management. Available online: https://www.academia.edu/33041792/When_BIM_becomes_a_LEAN_tool_approach_for_BIM_in_process_management (accessed on 1 May 2021).
14. Sacks, R.; Koskela, L. Interaction of lean and building information modeling in construction. *J. Constr. Eng. Manag.* **2010**, *136*, 968–980. [CrossRef]
15. Oskouie, P.; Gerber, D.J. Extending the interaction of building information modeling and lean construction. In Proceedings of the 20th Annual Conference of the International Group for Lean Construction, San Diego, TX, USA, 18–20 July 2012.
16. Alan, M.A. What is lean construction: Another look 2018. In Proceedings of the 26th Annual Conference of the International Group for Lean Construction, Chennai, India, 18–22 July 2018.
17. Tzortzopoulos, P.; Kagioglou, M. Theory of Lean Construction, production control systems for construction at the nexus of Lean and BIM. In *Lean Construction: Core Concepts and New Frontiers*; Routledge: New York, NY, USA, 2020; pp. 3–11, 54–82.
18. P2SL Glossary. Available online: https://p2sl.berkeley.edu/glossary/l/ (accessed on 1 May 2021).

19. Khanzode, A.; Fischer, M.; Reed, D.; Ballard, G. *A Guide to Applying the Principles of Virtual Design & Construction (VDC) to the Lean Project Delivery Process*; CIFE Publications: Stanford, CA, USA, 2014.
20. Ballard, G. Work Structuring. LCI White Paper # 5. 1999. Available online: http://p2sl.berkeley.edu/wp-content/uploads/2016/03/W005-Ballard-1999-Work-Structuring-Powerpoint-on-LCI-White-Paper-5.pdf (accessed on 1 May 2021).
21. Ballard, G.; Tommeleit, I. Lean construction tools and techniques. In *Design and Construction*, 1st ed.; Routledge: London, UK, 2007.
22. Ballard, G. The Last Planner System of Production Control. Ph.D. Thesis, University of Birmingham, Birmingham, UK, 2000. Available online: https://www.leanconstruction.org/media/docs/ballard2000-dissertation.pdf (accessed on 1 May 2021).
23. Evans, M.; Farrell, P. Barriers to integrating building information modelling (BIM) and lean construction practices on construction mega-projects: A Delphi study. *Benchmarking Int. J.* **2020**, *28*, 652–669. [CrossRef]
24. Fakhimi, A.; Sardroud, J.M. How can Lean, IPD and BIM work together? In Proceedings of the 33rd International Symposium on Automation and Robotics in Construction, Auburn, AL, USA, 18–21 July 2016.
25. Namli, E.; Isikdag, U. Building Information Management (BIM), A new approach to project management. *J. Sustain. Constr. Mater. Technol.* **2019**, *4*, 323–332. [CrossRef]
26. Volk, R.; Stengel, J. Building Information Modeling (BIM) for existing buildings—Literature review and future needs. *Autom. Constr.* **2013**, *38*, 109–127. [CrossRef]
27. Boton, C.; Kubicki, S. Maturité des pratiques BIM: Dimensions de modélisation, pratiques collaboratives et technologies. In Proceedings of the Interaction des Maquettes Numériques. Séminaire de Conception Architecturale Numérique Conference, Luxembourg, 18–20 June 2014. (In French)
28. Charef, R.; Alaka, H. Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views. *J. Build. Eng.* **2018**, *38*, 109–127. [CrossRef]
29. Information Delivery Manual: Guide to components and Development Methods. *Build. Smart Int.* 2010. Available online: https://standards.buildingsmart.org/documents/IDM/IDM_guide-CompsAndDevMethods-IDMC_004-v1_2.pdf (accessed on 1 May 2021).
30. Mohamedi, B. Définir le Niveau de Détail (LOD) de sa Maquette BIM. Available online: https://mydigitalbuildings.com/blog/tech/2020/comment-definir-le-niveau-de-detail-de-sa-maquette-n-merique.html#:~:text=Qu\T1\textquoterightest%2Dce%20qu\T1\textquoteright,objets%203D%20qui%20la%20constituent (accessed on 3 March 2020).
31. Vestermo, A.; Murvold, V. BIM Stations: What it is and how it can be used to implement Lean principles. In Proceedings of the 24th Annual Conference of the International Group for Lean Construction, Boston, MA, USA, 20–22 July 2016.
32. Dave, B.; Koskela, L. *Implementing Lean in Construction: Lean Construction and BIM*; CIRIA: London, UK, 2013.
33. Choo, H.J.; Tommelein, I. WORKPLAN: Constraint-based database for work package scheduling. *J. Constr. Eng. Manag.* **1999**, *125*, 151–160. [CrossRef]
34. Dave, B. Developing a Construction Management System Based on Lean Construction and Building Information Modeling. Ph.D. Thesis, Technion University, Haifa, Israel, 2013. Available online: http://usir.salford.ac.uk/id/eprint/30820/ (accessed on 1 May 2021).
35. Chua, D.K.H.; Shen, L.J.; Bok, S.H. Constraint-based planning with integrated production scheduler over internet. *J. Constr. Eng. Manag.* **2003**, *129*, 293–301. [CrossRef]
36. Sriprasert, E.; Dawood, N. Multi-Constraint Information Management and visualization for collaborative planning and control in construction. *Electron. J. Inf. Technol. Constr.* **2003**, *8*, 341–366.
37. Sacks, R.; Eastman, C. Introduction. In *BIM Handbook: A Guide to Building Information Modeling for Owners*, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2008; pp. 16–17.
38. Sacks, R.; Treckmann, M. Visualization of workflow to support Lean construction. *J. Constr. Eng. Manag.* **2009**, *18*, 469–484.
39. Sacks, R.; Radosavljevic, M. Requirements for building information modeling based Lean production management systems for construction. *Autom. Constr.* **2010**, *19*, 641–655. [CrossRef]
40. Rafael Sacks, R.S.; Ronen Barak, R.B. KanBIM workflow management system prototype implementation and field testing. *Lean Constr. J.* **2013**, *2013*, 19–35.
41. Dave, B.; Boddy, S. VisiLean: Designing a production management system with Lean and BIM. In Proceedings of the 19th Annual Conference of the International Group for Lean Construction, Lima, Peru, 13–15 July 2011.
42. Ballard, G.; Tommelein, I. Current Process Benchmark for the Last Planner System. Available online: http://p2sl.berkeley.edu/wp-content/uploads/2016/10/Ballard_Tommelein-2016-Current-Process-Benchmark-for-the-Last-Planner-System.pdf (accessed on 1 May 2021).
43. Information Technology. Available online: https://www.sciencedirect.com/topics/social-sciences/information-technology (accessed on 1 May 2021).
44. De Vries, B.; Harink, J.M.J. Generation of a construction planning from a 3D CAD model. *Autom. Constr.* **2007**, *16*, 13–18. [CrossRef]
45. Kataoka, M.K. Automated generation of construction plans from primitive geometries. *J. Constr. Eng. Manag.* **2008**, *134*, 592–600. [CrossRef]
46. Ibrahim, Y.M.; Lukins, T.C.; Zhang, X.; Trucco, E.; Kaka, A.P. Towards automated progress assessment of workpackage components in construction projects using computer vision. *Adv. Eng. Inform.* **2009**, *23*, 93–103. [CrossRef]

47. Kim, H.; Anderson, K.; Lee, S.; Hildreth, J. Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology. *Autom. Constr.* **2013**, *35*, 285–295. [CrossRef]
48. Liu, H.; Al-Hussein, M. BIM-based integrated approach for detailed construction scheduling under resource constraints. *Autom. Constr.* **2015**, *53*, 29–43. [CrossRef]
49. Wang, H.-W.; Lin, J.-R.; Zhang, J.-P. Work package-based information modeling for resource-constrained scheduling of construction projects. *Autom. Constr.* **2020**, *109*, 102958. [CrossRef]
50. Di Nardo, M.; Madonna, M. Modelling a safety management system using system dynamics at the bhopal incident. *Appl. Sci.* **2020**, *10*, 903. [CrossRef]
51. Di Nardo, M.; Gallo, M. System dynamics simulation for fire and explosion risk analysis in home environment. *Int. Rev. Model. Simul.* **2017**, *10*, 43–54. [CrossRef]
52. Kopsida, M.; Brilakis, I. A Review of Automated Construction Progress Monitoring and Inspection Methods. In Proceedings of the 32nd CIB W78 Conference on Construction IT, Eindhoven, The Netherlands, 26–29 October 2015.
53. Ham, Y.; Han, K.K.; Lin, J.J.; Golparvar-Fard, M. Visual monitoring of civil infrastructure systems via camera-equipped Unmanned Aerial Vehicles (UAVs): A review of related works. *Vis. Eng.* **2016**, *4*, 1. [CrossRef]
54. Golparvar-Fard, M.; Peña-Mora, F. Four-dimensional augmented reality models for interactive visualization and automated construction progress monitoring. *J. Inf. Technol. Constr.* **2013**, *14*, 129–153.
55. Lin, J.J.; Han, K. Framework for model-driven acquisition and analytics of visual data using uavs for automated construction progress monitoring. In Proceedings of the Conference Computing in Civil Engineering, Austin, TX, USA, 21–23 June 2015.
56. Karsch, K.; Golparvar-Fard, M. ConstructAide: Analyzing and visualizing construction sites through photographs and building models. *ACM Trans. Graph.* **2014**, *33*, 176. [CrossRef]
57. Ahuja, R.A.; Sawhney, A. Developing organizational capabilities to deliver Lean and green project outcomes using BIM. *Eng. Constr. Archit. Manag.* **2017**, *25*, 1255–1276. [CrossRef]
58. Schimanski, C.P.; Marcher, C.; Monizza, G.P.; Matt, D.T. The Last Planner® system and building information modeling in construction execution: From an integrative review to a conceptual model for integration. *Appl. Sci.* **2020**, *10*, 821. [CrossRef]
59. Schimanski, C.P.; Monizza, G.P.; Marcher, C.; Matt, D.T. Development of a BIM-based production planning and control system for Lean Construction through advancement and integration of existing management techniques. *Front. Eng. Manag.* **2020**, 1–13. [CrossRef]