Interaction of Lean and Building Information Modeling in Construction

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Abstract: Lean construction and building information modeling (BIM) are quite different initiatives, but both are having profound impacts on the construction industry. A rigorous analysis of the myriad specific interactions between them indicates that a synergy exists which, if properly understood in theoretical terms, can be exploited to improve construction processes beyond the degree to which it might be improved by application of either of these paradigms independently. Using a matrix that juxtaposes BIM functionalities with prescriptive lean construction principles, 56 interactions have been identified, all but four of which represent constructive interaction. Although evidence for the majority of these has been found, the matrix is not considered complete but rather a framework for research to explore the degree of validity of the interactions. Construction executives, managers, designers, and developers of information technology systems for construction can also benefit from the framework as an aid to recognizing the potential synergies when planning their lean and BIM adoption strategies.

DOI: 10.1061/(ASCE)CO.1943-7862.0000203

CE Database subject headings: Computer aided design; Construction management; Information technology (IT); Lean construction.

Author keywords: Computer aided design; Construction management; Information technology; Lean construction.

Introduction

Two major developments are effecting fundamental change in the architecture/engineering/construction industry. First is a conceptual approach to project and construction management—lean construction—and second is a transformative information technology—building information modeling (BIM). While the two are conceptually independent and separate, there appear to be synergies between them that extend beyond the essentially circumstantial nature of their approaching maturity contemporaneously. Their parallel adoption in state-of-the-art construction practice is a potential source of confusion when assessing their impacts and effectiveness. Does BIM, as a process, have features that would be intrinsically instrumental in eliminating dominant wastes in construction? Will the organizational forms stimulated by the introduction of BIM be neutral, conducive, or hindering regarding lean? What characteristics of BIM systems promote flow and what characteristics interrupt flow?

As a starting point, we define the two concepts for the specific purposes of the framework analysis (these should not be construed as an attempt to provide authoritative definitions but only to provide the proper context for the discussion that follows).

Lean Construction

Lean construction refers to the application and adaptation of the underlying concepts and principles of the Toyota Production System (TPS) to construction. As in the TPS, the focus in lean construction is on reduction in waste, increase in value to the customer, and continuous improvement. While many of the principles and tools of the TPS are applicable as such in construction, there are also principles and tools in lean construction that are different from those of the TPS.

BIM

The glossary of the BIM handbook (Eastman et al. 2008) defines BIM as "a verb or adjective phrase to describe tools, processes, and technologies that are facilitated by digital machine-readable documentation about a building, its performance, its planning, its construction, and later its operation." The result of BIM activity is a "building information model." BIM software tools are characterized by the ability to compile virtual models of buildings using machine-readable parametric objects that exhibit behavior commensurate with the need to design, analyze, and test a building design (Sacks et al. 2004). As such, three-dimensional (3D) computer-aided drafting (CAD) models that are not expressed as objects that exhibit form, function, and behavior (Tolman 1999) cannot be considered building information models.

However, the BIM handbook also states in its introduction that BIM provides "the basis for new construction capabilities and changes in the roles and relationships among a project team. When implemented appropriately, BIM facilitates a more integrated design and construction process that results in better quality buildings at lower cost and reduced project duration." In this

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Note. This manuscript was submitted on July 2, 2009; approved on February 8, 2010; published online on February 9, 2010. Discussion period open until February 1, 2011; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 136, No. 9, September 1, 2010. ©ASCE, ISSN 0733-9364/2010/9-968–980/$25.00.

sense, BIM is expected to provide the foundation for some of the results that lean construction is expected to deliver.

Lean construction and BIM are not dependent on one another (i.e., lean construction practices can be adopted without BIM, and BIM can be adopted without lean construction). This is illustrated by the numerous cases of separate adoption of each in design and construction companies within the past decade. However, we hypothesize that the full potential for improvement of construction projects can only be achieved when their adoption is integrated, as they are in the integrated project delivery (IPD) approach. A similar notion is expressed in the American Institute of Architects document on IPD (Eckblad et al. 2007), “Although it is possible to achieve IPD without BIM, it is the opinion and recommendation of this study that BIM is essential to efficiently achieve the collaboration required for IPD.”

The following sections of this paper provide a formal exposition of this idea by defining the interrelationships between the two. This is achieved by means of a framework that juxtaposes BIM functionalities and lean principles, establishes the theoretical relationships between them, and identifies the constructive and destructive interactions between them in implementation.

Emerging Research and Empirical Evidence Linking BIM and Lean Thinking

Liker (2003) has pointed out that Toyota remained flexible (in comparison with its competitors) by selecting only those information and communication technology (ICT) opportunities that were needed and which could reinforce the business processes directly and by ensuring through testing that they were an appropriate “fit” to the organizational infrastructure (people, process, and other ICT). BIM provides this opportunity to the construction industry because it reinforces the core construction processes. However, to date, the results of much of the construction industry’s investment in ICT have been less than satisfactory for a number of reasons (Dave et al. 2008). The main factors are the following:

- Too much emphasis has been placed on solutions which focus mainly on peripheral issues (such as enterprise resource planning systems) rather than core processes.
- The three core organizational issues—people, process, and technology—have not been addressed with the required balance.

The individual areas of lean construction and BIM have been researched extensively in recent years. However, there seems to be much less research that exploits both of these areas collectively. The following paragraphs describe efforts that explore the synergy between the areas of BIM and lean construction.

In an attempt to evaluate the impact of what they termed “computer advanced visualization tools” (CAVTs), Rischmoller et al. (2006) used a set of lean principles as the theoretical framework. They placed key emphasis on value generation during the design stage of the construction project. Based on a case study conducted over a four-year period, they concluded that application of CAVT results in waste reduction, improved flow, and better customer value, indicating a strong synergy between the lean construction principles and CAVT.

In another effort to integrate lean construction processes with BIM, Khanzode et al. (2006) attempted to provide a conceptual framework to link virtual design and construction (VDC) with the lean project delivery process (LPDS). As with CAVT, the VDC concept can be taken to represent BIM or aspects of BIM due to the similarities in underlying principles and technologies. Here too, results from a case study confirmed that the application of VDC enhances the lean project delivery process when applied at the correct stages. The writers reported that there was hitherto no literature on linking BIM to the lean construction process, and so provided an initial set of guidelines.

Sacks et al. (2009) discussed the potential contributions of BIM to visualization of the product and process aspects of construction projects in terms of lean construction principles. They provided examples that illustrate the use of BIM and related technologies to enable a “pull flow” mechanism to reduce variability within the construction process.

IPD and VDC are emerging techniques that leverage BIM to provide an integrated project management and collaboration platform. The first places emphasis on engendering collaboration through a central common contract, while the latter focuses primarily on skilled use of information technology. Both are still in their infancy, but they are being developed and their adoption within the industry is increasing. Some of the major process changes that have been documented are (Eastman et al. 2008, Ch. 1; Khemlani 2009) the following:

1. Increased engagement of construction knowledge and skill upstream in the design process;
2. Development of detailed design earlier than has been common with traditional systems;
3. Collocated teams;
4. Contractual arrangements to share pain and gain; and
5. Introduction of new roles, such as BIM managers or consultants.

Khemlani (2009) reported a detailed case study of a project in which IPD was implemented. The Sutter Health Castro Valley Medical Center project, a $320 million hospital building facility, builds on the project team’s earlier experience implementing BIM and lean on projects such as the Camino Medical Center (Eastman et al. 2008, p. 358). Each design and construction partner uses the BIM system of their choice for design and/or fabrication detailing. The discipline models are then integrated using collaboration software for coordination and the design is tested for code compliance using Solibri model checker. The team also uses lean tools such as value stream mapping to monitor and improve the project processes, which aims to minimize the cycles of iteration as the design converges. On this project a unique professional role, defined as “lean/BIM project integrator,” has been created. The positive results reported to date demonstrate how the new project management process combines the areas of lean and BIM to leverage maximum benefit.

Gilligan and Kunz (2007) reported that the use of VDC in an earlier project was considered to contribute directly to the implementation of lean construction methods: “Early interaction between the design and construction teams, driven by the owner Sutter Health’s Lean Construction delivery process, used 3D models to capitalize on true value engineering worth nearly $6 million.” Khanzode et al. (2005) provided additional descriptions of the project and the use of VDC and lean methods in its construction.

Eastman et al. (2008, Ch. 9) provided 10 detailed case studies of BIM implementation, two of which focus on projects in which prefabrication was used extensively. In the context of detailed design for fabrication and delivery by subcontracted suppliers of prefabricated elements, they comment that “Lean construction techniques require careful coordination between the general contractor and subs to ensure that work can be performed when the appropriate resources are available on site. … Because BIM pro-

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vides an accurate model of the design and the material resources required for each segment of the work, it provides the basis for improved planning and scheduling of subcontractors and helps to ensure just-in-time arrival of people, equipment, and materials." It emerges from this review of existing literature and research efforts that even if many interesting connections have been pinpointed, there is a lack of systematic exploration between BIM and lean construction and that further efforts are needed to bridge this gap in knowledge.

Relevant Lean Construction Principles

Several authors have provided lists of lean principles, both in the general lean production literature (Liker 2003; Schonberger 1996; Womack and Jones 2003) and the lean construction literature (Koskela 1992, 2000). In this context, it is also worth mentioning Deming's 14 points that are based on the quality approach (Deming 1982). In the following, we present a list that has been specifically compiled for the analysis of interconnections between lean and BIM.

In selecting such principles, a number of criteria were used. Regarding the focus of the principles, it is interesting to consider the four types of principles, as defined by Liker: philosophy; process; people and partners; and problem solving. From these, only principles relating to philosophy are assumed not to relate to BIM. Another choice concerns whether the principles should be descriptive or prescriptive. For example, Hopp and Spearman (1996) presented a number of descriptive manufacturing laws, whereas most lean authors have prescriptive principles. Here, the mainstream approach has been adapted, and the applicable descriptive laws have been transformed into prescriptive principles.

A further choice is about the meaning of "process." As it has been contended elsewhere (Koskela 2004b), popular accounts, such as Womack and Jones (2003), may confound the two involved concepts, namely, flow and value generation, and thus blur the existence of two conceptualizations from which principles are being derived. Historically, lean was initiated based on the flow concept, and the value concept, cultivated by the quality movement, was later merged into lean. Here, principles are explicitly derived from both concepts. With the exception for some key relationships, the complex interrelations between the principles are not discussed in this short account. Each principle is presented in generic terms, but if its application in construction deviates from the mainstream, the construction-specific features are briefly commented upon.

In the following paragraphs the principles are listed in bold, with detailed prescriptions noted in italics:

Reduce Variability. This is a foundational principle that has been derived through two domains, industrial engineering and quality engineering. In statistical quality theory (Shewhart 1931), the target is to *reduce the variability in the significant product characteristics*. In queuing theory based understanding of production (Hopp and Spearman 1996), the target is to *reduce temporal variability of production flows*. These two types of variability interact in a complex way.

Reduce Cycle Times. Because variability expands cycle times, this principle can be used as a driver toward variability reduction. However, reduction in cycle times also has intrinsic value. Due to the definitional connection between work in progress and cycle time (expressed in Little's law), this principle is roughly equivalent to *inventory reduction*. In construction, reduction in cycle times should be focused on several levels of analysis: total construction duration, stage of construction, flow of materials (from factory to installation), and task (Koskela 2000).

Reduce Batch Sizes. Or *striving for single piece flow* is an effective technique for reducing the expansion of cycle times due to batching. In construction, abstract conceptualizations of "products" that can be counted in a batch are needed. These are commonly predefined as packaged sets of tasks performed in distinct spaces, such as apartments (Sacks and Goldin 2007).

Increase Flexibility. Here flexibility may be associated with work station capability and capacity, routings, etc. Flexibility reduces cycle times simplifies the production system. In construction, *multiskilled teams* provide an example. *Reduced setup or changeover times* increase routing flexibility with short cycle times.

Select an Appropriate Production Control Approach. In a pull system, a productive activity is triggered by the demand of a downstream work station (or customer), whereas in a push system, a plan pushes activities into realization. The *pull system* has come to be closely associated to lean. However, in reality most production control systems are mixed push-pull systems, and the task is to select the best method for each stage of production (Huang and Kusiak 1998). *Leveling of production* facilitates the operations of a pull system. In construction, the push system is realized through plans and schedules. The look-ahead procedure in the last planner system of production control provides an example of pulling.

Standardize. Standardization of work serves several goals. Both temporal and product feature variability can be reduced, and continuous improvement is enabled. Employees are also empowered to improve their work.

Institute Continuous Improvement. Through continuous improvement, variability can be reduced, and also technology incrementally improved. The foundation for continuous improvement was provided by the scientific experimentation method for improvement (Shewhart 1931) and is now known under the name of Deming cycle. Continuous improvement is a deliberate, institutionalized, and systematic form of improvement and thus in many ways goes beyond mere learning (as addressed by the concept of the learning curve).

Use Visual Management. Visual management is closely connected to standardization, where *visualization of production methods* offers easy access to standards and supports compliance with them. It is also closely connected to continuous improvement in that *visualization of production processes* enables perception by workers of the process state and of measures of improvement.

Design the Production System for Flow and Value. This principle stresses the importance of production system design (this phrase is also intended to cover the product development and design stage). Generally, criteria derived from the two concepts of production should be used in this endeavor. Another important issue is that production system design should support production control and continuous improvement. There are several heuristics for production system design, advising toward *simplification*, use of *parallel processing*, and *use of only reliable technology*. From the viewpoint of value, *ensuring the capability of the production system* is important.

Ensure Comprehensive Requirements Capture. This is the first principles addressing solely the value generation concept. For obvious reasons, value generation requires comprehensive requirements capture—in practice, this is a notoriously problematic stage (Kamara et al. 2002).

Focus on Concept Selection. Designing divides into concept design and detail design. The development of different concepts and their evaluation should be addressed with necessary emphasis, as there is a natural tendency to rush to detail design. Set based design is an application of this principle that is useful for building design (Parrish et al. 2007).

Ensure Requirements Flow down. The next challenge from the point of view of value generation is to ensure that all requirements flow down to the point where the smallest parts of the product are designed and produced.

Verify and Validate. Also in the realm of value generation, this principle, well known from the V model of system engineering (Stevens et al. 1998), reminds us that intent is not enough. All designs and products should be verified against specifications and validated against customer requirements.

Go and See for Yourself. This "going to Gemba" principle stresses the importance of personal observation instead of reports and hearsay (Liker 2003). Although traditionally in construction the tendency has been to solve problems in situ, this principle tends to stress the importance of site visits of those who usually do not practice them, for example, estimators and managers.

Decide by Consensus, Consider All Options. This principle derives from the practice of Toyota (Liker 2003). By extending the circle of decision makers, a wider knowledge base can be ensured for the decisions. By extending the number of options considered, the probability of finding the practically best solution is increased.

Cultivate an Extended Network of Partners. This principle implies that an extended network of partners should be built, challenged, and helped to improve. In construction, this can either happen in the framework of one project (alliancing) or on a longer term basis (framework agreements).

BIM Functionality

We next identify the relevant key aspects of functionality that BIM technology provides for compiling, editing, evaluating, and reporting information about building projects. The fundamental technology that is the basis of most of the functionality shared by all BIM tools is parametric object modeling and application of parametric constraints (Sacks et al. 2004). Object modeling implies the use of software objects, which group data and the methods to manipulate them, to represent real-world concepts (Galle 1995). The concepts may be physical, such as parts of a building, or abstract, such as a cost estimate or a structural analysis result (Turk et al. 1994). The adjectives "parametric object" imply the possibility to reuse object "class" definitions to represent multiple occurrences of similar things; these are termed "instances" of a class and have different attribute values but the same basic structure. Inheritance of class attributes and methods in a hierarchy makes it possible to build extensive taxonomies of objects, with complex behaviors, fairly efficiently. Parametric constraints, which are applied to the resulting model object instances, enable expression and application of rules that govern the way the objects behave when manipulated, so that they can be programmed to respond to actions on them in the way that we would expect their real-world counterparts to behave. For example, when a wall is moved in a BIM design tool, we naturally expect a door within it to move with it. In summary, it is this technology that enables BIM tools to model building's form, function, and behavior (Tolman 1999) and that makes all of the aspects of functionality listed below possible.

For the purposes of the analysis, we focus on the exhibited functionality rather than the core technology. The items listed in the following text have been phrased with care to express bare functionality, avoiding a priori assumptions concerning the potential benefits or drawbacks of their use in relation to lean construction principles. They are drawn primarily from Eastman et al. (2008) and Sacks et al. (2004).

Visualization of Form (for Aesthetic and Functional Evaluation). All BIM systems provide the ability to render the designs with some degree of realism, making building designs more accessible to nontechnical project participants and stakeholders than is possible with technical drawings.

Rapid Generation of Multiple Design Alternatives. Designers can manipulate design geometry efficiently by taking advantage of the parametric relationships and behavioral "intelligence," which maintain design coherence, and of automated generation and layout of detailed components (e.g., automated connection detailing in steel construction). This was not possible with CAD systems.

Use of Model Data for Predictive Analysis of Building Performance. This has three aspects:

1. Some BIM software products have engineering analysis tools (such as finite-element and energy analyses) built in and most can export relevant preprocessed data for import to external third-party analysis tools. Varying degrees of human effort are needed to adapt the exported data to the forms required by the analysis tools, and different degrees of rework are required to change the analysis models whenever the building model is changed. Nevertheless, the procedures are more productive, less error prone, and quicker than compilation of the analysis models from scratch.
2. Automated life cycle and construction cost estimation with links to online sources of cost data.
3. Automated evaluation of conformance to program/client value and code compliance checking using rule processing. A recent comprehensive review (Eastman et al. 2009) shows that while this functionality is still limited in scope, its development is well beyond the proof of concept stage.

Maintenance of Information and Design Model Integrity. This capability is achieved because BIM tools *store each piece of information once*, without the repetition common in drawing systems where the same design information is stored in multiple drawings or drawing views (such as on a plan, an elevation, and a detail sheet). Geometric integrity is also enhanced where the *automatic clash-checking* capabilities of model integra-

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tion software tools are used to identify and remove physical clashes between model parts.

Automated Generation of Drawings and Documents. Different BIM softwares offer varying degrees of automation for initial generation of drawings and documents, with most needing at least some user input for custom annotation. By definition, however, a BIM system is one that automatically propagates any model changes to the reports, thus automatically maintaining integrity between the model and the reports (Eastman et al. 2008, p. 16). Some, but not all, also offer full bidirectional editing, where the model can be edited directly from model object links embedded in drawings.

Collaboration in Design and Construction. Collaboration in design and construction is expressed in two ways: "internally," where *multiple users within a single organization or discipline edit the same model simultaneously*, and "externally," where *multiple modelers simultaneously view merged or separate multidiscipline models* for design coordination. Whereas in the internal mode objects can be locked to avoid inconsistencies when objects might be edited to produce multiple versions, in the external mode only noneditable representations of the objects are shared, avoiding the problem but enforcing the need for each discipline to modify its own objects separately before checking whether conflicts are resolved.

Rapid Generation and Evaluation of Construction Plan Alternatives. Numerous commercial packages are available for four-dimensional (4D) visualization of construction schedules. Some automate the generation of construction tasks and modeling of dependencies and prerequisites (such as completion of preceding tasks, space, information, and safety reviews) and resources (crews, materials, equipment, etc.) by using libraries of construction method recipes, so that changes to plans can be made and evaluated within hours. Although the use is not widespread, some provide functions that enable discrete event simulation of construction procedures and plans. Such developments permit construction process rehearsal and iterative optimization (Kong and Li 2009; Li et al. 2009).

Online/Electronic Object-Based Communication. At present, online communication is largely limited to the use of project intranets and more advanced *model servers*. However, more sophisticated systems that integrate product information in BIM tools with process information from enterprise-wide information systems have moved beyond early research and have been implemented [e.g., ConstructSim (Bentley, Exton, Pa.) for process plants]. These newer tools enable *visualizations of process and product status* using the graphic building model views to deliver the information to workers in construction environments (Sacks et al. 2009). LEWIS (Sriprasert and Dawood 2003) and the KanBIM system (Sacks et al. 2010), which delivers integrated product and process information directly, are examples from research. In the near future, these systems will also use building model views to provide the context for collection of *status data* on and off sites.

Direct Information Transfer to Support Computer-Controlled Fabrication. Direct information transfer to support computer-controlled fabrication of construction components (rebar, structural steel members, etc.) using numerically controlled machines is already common. Similarly, *business-to-business integration between companies* collaborating in construction projects is also possible on the basis of product specifications that originate in building models.

Research Framework for Analysis of the Interaction of Lean and BIM

The lean principles listed in Table 1 and the features of BIM functionality listed in Table 2 were arranged in a matrix, as shown in Table 3. The bare matrix, without cell entries, is a framework for analysis of the interactions between BIM functionality and lean principles. The nature of the interaction in any cell may be positive, representing synergy between BIM and lean construction, or negative, where the use of BIM inhibits implementation of a lean principle. The goal of the framework is to both guide and stimulate research; as such, the approach adopted up to this point is constructive.

BIM–Lean Influence Analysis

The next steps in using the framework are (1) to postulate possible interactions and (2) to seek empirical evidence to either support or refute them. In this section, we propose 56 distinct interactions on the basis of the emerging evidence from research and practice outlined in the literature survey earlier in the paper. Some are drawn directly from the evidence and others are inferred based on the informed reasoning of the writers. The impact of each feature of BIM functionality on each lean principle was assessed according to the definitions provided for the functionality and principles. The numbers listed in the cells of Table 3 are indices to the explanations of the cell interactions that appear in Table 4. Positive numbers indicate positive interaction, while the indices shown in brackets represent negative interaction.

The explanations provided for each interaction (listed in Table 4) postulate the possible interactions. They are not deemed to be proven by empirical evidence but rather they are candidates for verification or contradiction through measurement in future research. Where anecdotal or other evidence is available, the appropriate sources are referenced in the third column. Where documented evidence has not been found, we have noted "not yet available"; these areas are potentially fertile ground for future empirical research to substantiate or refute the interactions.

Discussion

Reviewing the matrix (Table 3) reveals a number of aspects of interest in terms of concentrations of positive and negative interactions for specific BIM functionalities and lean principles. These lead to observations and recommendations for guiding management focus when implementing lean and BIM, but they also provoke reflection on the depth of understanding that may be needed for managers to realize the positive interactions in practice.

The lean principles that have the highest concentration of unique interactions are "get quality right the first time (reduce product variability)" (A), "focus on improving upstream flow variability (reduce production variability)" (B), and "reduce production cycle durations" (C). These have significantly more numerous interactions than any of the other principles. Interestingly, the interactions are not limited to the BIM functionalities that serve design activities but rather their impact is felt across design and construction.

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Table 1. Lean Principles

Principal area	Principle	Column key
Flow process	**Reduce variability**	
	Get quality right the first time (reduce product variability)	A
	Focus on improving upstream flow variability (reduce production variability)	B
	Reduce cycle times	
	Reduce production cycle durations	C
	Reduce inventory	D
	Reduce batch sizes (strive for single piece flow)	E
	Increase flexibility	
	Reduce changeover times	F
	Use multiskilled teams	G
	Select an appropriate production control approach	
	Use pull systems	H
	Level the production	I
	Standardize	J
	Institute continuous improvement	K
	Use visual management	
	Visualize production methods	L
	Visualize production process	M
	Design the production system for flow and value	
	Simplify	N
	Use parallel processing	O
	Use only reliable technology	P
	Ensure the capability of the production system	Q
Value generation process	**Ensure comprehensive requirement capture**	R
	Focus on concept selection	S
	Ensure requirement flow down	T
	Verify and validate	U
Problem solving	**Go and see for yourself**	V
	Decide by consensus, consider all options	W
Developing partners	**Cultivate an extended network of partners**	X

The BIM functionalities that have the highest concentrations of unique interactions are "aesthetic and functional evaluation" (1), "multiuser viewing of merged or separate multidiscipline models" (10), "4D visualization of construction schedules" (13), and "online communication of product and process information" (15). Although the distinction between these and the other functionalities is not as sharp as it is for the leading lean principles, we note that three of these four are concerned with fabrication and construction management despite the fact that BIM is perceived by many to be primarily a design tool.

The principles that appear to be served least or even negatively impacted are "reduce inventory" (D), "simplify production systems" (N), and "use only reliable technology" (P). BIM can increase information inventory if not used in a process that actively streamlines information flow. Because BIM tools are technologically sophisticated, if not properly implemented and managed they can make a process more complicated and unstable if the applications are not mature or if the users are not competent. Similarly, consumers of model information may place undue trust in the accuracy of models; models are often incomplete and have different degrees of detail in different zones or buildings systems. The BIM functionality that offers least in terms of support for lean principles is the single information source (6).

The preponderance of positive interactions over negative interactions that is apparent from Tables 3 and 4 should not lead readers to assume that their achievement in practice is straightforward. Realization of the benefits in practice cannot be taken for granted. Numerous studies have shown that application of information technology in construction management has in certain circumstances failed to provide a positive return on investment. In a Scandinavian study, Howard et al. (1998) found benefits in design and administration but not in construction management per se. Rivard's results for Canada were similar (Rivard 2000), and Gann pointed out that the costs could outweigh the benefits in certain circumstances (Gann 2000). Underutilization and interoperability issues have been identified as key problems with BIM adoption (Fox 2008), and lack of conceptual understanding can be a barrier to lean construction initiatives.

In analyzing this situation, Koskela and Kazi (2003) started by introducing the notion that realizing information technology benefits in general is dependent on compatible realignment of business processes. They then build on this in the construction context to suggest that such realignment is itself predicated on the need for a fundamental understanding of the peculiarities of construction. In the current context of lean construction and BIM, we propose that for comprehensive realization of benefits, not only should changes in information and material processes be coherently based on these two but that all three—process changes, BIM

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Table 2. BIM Functionality

Stage	Functional area and function	Row key
Design	**Visualization of form**	
	Aesthetic and functional evaluation	1
	Rapid generation of multiple design alternatives	2
	Reuse of model data for predictive analyses	
	Predictive analysis of performance	3
	Automated cost estimation	4
	Evaluation of conformance to program/client value	5
	Maintenance of information and design model integrity	
	Single information source	6
	Automated clash checking	7
	Automated generation of drawings and documents	8
Design and fabrication detailing	**Collaboration in design and construction**	
	Multiuser editing of a single discipline model	9
	Multiuser viewing of merged or separate multidiscipline models	10
Preconstruction and construction	**Rapid generation and evaluation of construction plan alternatives**	
	Automated generation of construction tasks	11
	Construction process simulation	12
	4D visualization of construction schedules	13
	Online/electronic object-based communication	
	Visualizations of process status	14
	Online communication of product and process information	15
	Computer-controlled fabrication	16
	Integration with project partner (supply chain) databases	17
	Provision of context for status data collection on site/off site	18

tools themselves, and of course lean construction principles—should be rooted in conceptual understanding of the theory of production in construction. This is illustrated in Fig. 1.

By way of example, consider the significant shortening of cycle time that is commonly achieved when quantity takeoff is extracted from a building model, as compared with traditional measurements from drawings. This can be exploited to improve the value generated through iterative design refinement, but only if managers recognize (a) that the shortened cycle time shifts the bottleneck in the process to other activities and (b) that the overall design management approach can be realigned to bring designers and estimators to work together. Thus cycle time is reduced by BIM whether project participants are aware of it or not, but comprehensive benefits can only be achieved when its meaning is perceived clearly.

A second note of caution in interpreting the interaction matrix is that despite the analytical method inherent in the interaction matrix—i.e., subdivision of the whole into parts (cells of interaction)—the interaction of lean principles and BIM in construction should be seen as a whole and complex process rather than the sum of the isolated parts. Each functionality supports multiple lean principles and vice versa, and these presumably have a synergistic effect. For the same reason, expert reasoning cannot determine all of the interactions and their impacts; some will only emerge through exploration and trialing by practitioners.

The topics of BIM as a boundary object and construction tolerances, neither of which is included in the interaction matrix, are examples of such holistic interactions. Based on the seminal work by Star and Griesemer (1989), BIM technology has been identified as a boundary object in business and social interactions between construction professionals that requires, but can also facilitate organizational change (Forgues et al. 2009; Taylor 2005). As such, BIM technology could also be used as an enabler or catalyst for lean transformation. However, at present little is known about this issue.

Dimensional tolerances are not managed well in construction (Milberg 2006; Tsao et al. 2004). BIM may provide an opportunity for improved control of spatial tolerances through advanced tolerance analysis and management capabilities, which were previously unavailable in two-dimensional CAD software. It can also support prefabrication and assembly of high tolerance components. Higher precision tolerances would contribute to leaner processes as they arguably reduce variability and the resultant waste from the construction process as well as generally diminish the losses due to deviations from target values (Taguchi 1993). However, the potential impact is broad and indirect and remains to be proven through experimentation or empirical evidence.

Conclusions

At the outset, the different ways of conceptualizing lean construction (including the whole project life cycle) and BIM as presented in prior literature were examined. Based on this, a framework or taxonomy of analyses was created for assessing the interconnec-

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Table 3. Interaction Matrix of Lean Principles and BIM Functionalities

		Lean principles																							
		Reduce variability		Reduce cycle times		Reduce batch sizes	Increase flexibility		Select an appropriate production control approach		Standardize	Institute continuous improvement	Use visual management		Design the production system for flow and value				Ensure comprehensive requirements capture	Focus on concept selection	Ensure requirements flow down	Verify and validate	Go and see for yourself	Decide by consensus consider all options	Cultivate an extended network of partners
BIM functionality		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
Visualization of form	**1**	1,2													3				4		11	5	6	4	
Rapid generation of design alternatives	**2**	1		22									7	7		8									
Reuse of model data for predictive analyses	**3**	9	9	22			51												1	16		5			
	4		10	12												8				16		5			
	5	1,2	1	12															1	1	1	5			
Maintenance of information and design model integrity	**6**	11	11																		11				
	7	12	12	22																		12			
Automated generation of drawings and documents	**8**	11		22	(52)	53											54	54							
Collaboration in design and construction	**9**			23						36						36									
	10	2,13		24				33											43		56	46		49	
Rapid generation and evaluation of multiple construction plan alternatives	**11**	14		25	(29)		31								(41)										
	12		15	25	(29)					37					(41)					44		47			
	13	2	40	25	(29)						17		40	40		40						47		49	
Online/electronic object-based communication	**14**		29	26	30	30			34					34			(42)					47	48		
	15	18		26	30	30			34		38		38	34			(42)				45			49	
	16	19		27			32																		
	17		20	28					35								(42)								50
	18		21		30	30			34			39					(42)					47	48		

Note: Numbers in the cells are indexes to the cell content explanations provided in Table 4 and numbers in brackets represent negative interactions.

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Table 4. Interaction Matrix: Explanations of Cell Contents

Index	Explanation	Evidence from practice and/or research
1.	Due to better appreciation of design at an early stage, and also due to the early functional evaluation of design against performance requirements (such as energy, acoustics, wind, thermal, etc.) the quality of the end product is higher and more consistent with design intent. This reduces variability commonly introduced by late client-initiated changes during the construction stage.	Eastman et al. 2008, p. 390; Manning and Messner 2008
2.	Building modeling imposes a rigor on designers in that flaws or incompletely detailed parts are easily observed or caught in clash checking or other automated checking. This improves design quality, preventing designers from "making do" (Koskela 2004a) and reducing rework in the field as a result of incomplete design.	Dehlin and Olofsson 2008; Eastman et al. 2008, p. 422
3.	Building systems are becoming increasingly complex. Even trained professionals have difficulty generating accurate mental models with drawings alone. BIM simplifies the task of understanding designs, which helps construction planners deal with complex products.	Eastman et al. 2008, p. 382
4.	As all aspects of design are captured in a 3D model the client can easily understand; the requirements can be captured and communicated in a thorough way already during the concept development stage. This can also empower more project stakeholders to participate in design decision making.	Eastman et al. 2008, p. 378; Manning and Messner 2008
5.	Virtual prototyping and simulation due to the intelligence built in the model objects enable automated checking against design and building regulations, which in turn make verification and validation of the design more efficient.	Eastman et al. 2008, p. 390; Khanzode et al. 2008
6.	With BIM, Gemba can be augmented because it is now possible to virtually visit the project and the worksite (Whyte 2002). With objects that contain intelligence and parametric information, problem solving is also more efficient.	Whyte 2002
7.	BIM provides the ability to evaluate the impact of design changes on construction in a visual manner that is not possible with traditional 2D drawings. Rapid manipulation is a key enabler for repetition of this kind of analysis for multiple design alternatives (see also Item 40).	Eastman et al. 2008, p. 378
8.	It is now possible for multiskilled teams to work concurrently in order to generate various design alternatives at an early stage using integration platforms such as Navisworks, Solibri, etc., as exemplified in the Castro Valley project case study (Khemlani 2009). Also, at a later stage during manufacturing/construction; for any design change, changing the model will automatically update other relevant information such as cost estimating, project planning, production drawings, etc.	Eastman et al. 2008, p. 329; Khemlani 2009
9.	Testing the design against performance criteria ensures that the design is appropriate for the chosen function, reducing the variability and improving the performance of the end product.	Eastman et al. 2008, p. 390
10.	Automated quantity takeoff which is linked to the BIM model is more accurate as there are less chances of human error; hence, it improves flow by reducing variability. Also, changing the design at a later stage also changes the linked quantity files; this ensures that the quantities are always accurate.	Eastman et al. 2008, p. 425
11.	In sets of 2D drawings and specifications, the same objects are represented in multiple places. As design progresses and changes are made, operators must maintain consistency between the multiple representations/information views. BIM removes this problem entirely by using a single representation of information from which all reports are derived automatically.	Eastman et al. 2008, p. 422
12.	Use of software capable of model integration (such as Solibri/Navisworks/Tekla) to merge models, identify clashes, and resolve them through iterative refinement of the different discipline specific model results in almost error free installation on site.	Eastman et al. 2008, p. 431
13.	Multidisciplinary review of design and of fabrication detailing, including clash checking, enables early identification of design issues.	Eastman et al. 2008, p. 362; Khanzode et al. 2008
14.	Automated task generation for planning helps avoid human errors such as omission of tasks or work stages.	Eastman et al. 2008, p. 409
15.	Discrete event simulation can be used to test and improve production processes and to run virtual first-run studies which in construction are often impossible or impractical.	Eastman et al. 2008, p. 429
16.	At the conceptual design stage, rapid turnaround to prepare cost estimates and other performance evaluations enables evaluation of multiple design options, including the use of multiobjective optimization procedures (such as genetic algorithms).	Eastman et al. 2008, p. 445
17.	Animations of production or installation sequences can be prepared. These guide workers in how to perform work in specific contexts and are an excellent means for ensuring that standardized procedures are followed, particularly where turnover of workers from stage to stage is high, as is common in construction.	Eastman et al. 2008, p. 429
18.	When up-to-date product information is available online, the opportunities for identifying conflicts and errors within short cycle times, when their impact is limited, are enhanced.	Eastman et al. 2008, p. 422

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Table 4. (*Continued.*)

Index	Explanation	Evidence from practice and/or research
19.	Direct transfer of fabrication instructions to numerically controlled machinery, such as automated steel or rebar fabrication, eliminates opportunities for human error in transcribing information.	Khanzode et al. 2008; Tekla 2009b
20.	Direct delivery of information removes waiting time, thus improving flow.	Khemlani 2009
21.	Provision of a model background and context for scanning bar codes or RFID tags and display of the process data on model backgrounds enable accurate reporting and rapid response to work flow problems.	Vela 2009
22.	Quick turnaround of structural, thermal, and acoustic performance analyses; of cost estimation; and of evaluation of conformance to client program, all enable collaborative design, collapsing cycle times for building design, and detailing.	Eastman et al. 2008, p. 386
23.	Parallel processing on multiple workstations in a coordinated fashion (with locking of elements edited on each machine) collapses cycle times of otherwise serial design activities. Where design was previously (i.e., with CAD) performed in parallel on different parts, the time needed for integration and coordination of the different model views is removed.	Khemlani 2009
24.	Model-based coordination between disciplines (including clash checking) is automated and so requires a fraction of the time needed for coordination using CAD overlays.	Eastman et al. 2008, p. 422
25.	All three functions serve to reduce cycle time during construction itself because they result in optimized operational schedules, with fewer conflicts.	
26.	Where process status is visualized through a BIM model, such as in the KanBIM system, series of consecutive activities required to complete a building space can be performed one after the other with little delay between them. This shortens cycle time for any given space or assembly.	Sacks et al. 2010
27.	Direct computer-controlled machinery fed directly from a model can help shorten cycle times by eliminating labor-intensive data entry and/or manual production, thus shortening cycle times. This does not guarantee shortened cycle times if the time gained is then wasted through batching or waiting.	Eastman et al. 2008, p. 333
28.	Removal of data processing steps for ordering or renewing material deliveries, removal of time wasted before ordering, etc., improve cycle times.	Vela 2009
29.	In this case the functionality can be said to increase inventory of design alternatives. This can be considered beneficial in terms of making broader selections, delaying selection of a single alternative until the last responsible moment.	Khemlani 2009
30.	Online visualization and management of process can help implement production strategies designed to reduce work-in-process inventories and production batch sizes (number of spaces in process by a specific trade at any given time), as in the KanBIM approach.	Sacks et al. 2009
31.	Automated generation of tasks for a given model scenario and project status drastically reduces the setup time needed for any new computation or evaluation of a construction schedule alternative from any point forward.	Eastman et al. 2008, p. 345
32.	For numerically controlled machinery, data entry represents setup time. Direct electronic communication of process instructions from a model essentially eliminates this setup time, making single piece runs viable.	Tekla 2009b
33.	Design coordination between multiple design models using an integrated model viewer in a collaborative work environment, such as those described by Liston et al. (2001) and Khanzode et al. (2006), enables design teams to bring multidisciplinary knowledge and skills to bear in a parallel process.	Khanzode et al. 2006; Liston et al. 2001
34.	Process visualization and online communication of process status are key elements in allowing production teams to prioritize their subsequent work locations in terms of their potential contribution to ensuring a continuous subsequent flow of work that completes spaces, thus implementing a pull flow. This is central to the KanBIM approach, which extends the last planner system.	Sacks et al. 2009
35.	Where BIM systems are integrated with supply chain partner databases, they provide a powerful mechanism for communicating signals to pull production and delivery of materials and product design information. This also helps make the supply chain transparent.	Vela 2009
36.	Multiple users working on the same model simultaneously enable sharing of the workload evenly between operators.	Not yet available
37.	Discrete event simulation can reveal uneven work allocations and support assessment of work assignments to level production.	Li et al. 2009
38.	Online access to production standards, product data, and company protocols helps institutionalize standard work practices by making them readily available and, within context, to work teams at the work face. This relies, however, on provision of practical means for workers to access online information.	Hewage and Ruwanpura 2009; Sacks et al. 2010; Sriprasert and Dawood 2003

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Table 4. (*Continued.*)

Index	Explanation	Evidence from practice and/or research
39.	Where BIM interfaces provide a context for real-time status reporting, measuring performance becomes accurate and feasible. Measurement of performance within a system where work is standardized and documented is central to process improvement.	Not yet available
40.	BIM provides an ideal visualization environment for the project throughout the design and construction stage and enables simulation of production methods, temporary equipment, and processes. Modeling and animation of construction sequences in "4D" tools provide a unique opportunity to visualize construction processes for identifying resource conflicts in time and space and resolving constructability issues. This enables process optimization improving efficiency and safety and can help identify bottlenecks and improve flow.	Eastman et al. 2008, p. 429; Li et al. 2009
41.	Detailed planning and generation of multiple fine-grained alternatives can be said to increase complexity rather than simplify management.	Not yet available
42.	These applications cannot be considered mature technology.	Manning and Messner 2008
43.	Where clients or end users are engaged in simultaneous reviews of different system design alternatives they can more easily identify conflicts between their requirements and the functionality the proposed systems will provide.	Eastman et al. 2008, p. 349
44.	Rapid generation of production plan alternatives can allow selection among them to be delayed (making the last responsible moment later than it would be otherwise). This can be considered to be a set-based approach to production system design and to production planning.	Kong and Li 2009
45.	Online access helps to bring the most up-to-date design information to the work face (although it cannot guarantee that the design information reflects the user requirements).	Hewage and Ruwanpura 2009
46.	Clash checking and solving other integration issues verify and validate product information.	Li et al. 2009
47.	Visualization of proposed schedules and visualization of ongoing processes verify and validate process information.	Dehlin and Olofsson 2008
48.	Where managers can "see" process status with near to real-time resolution, this may substitute for the need to see processes directly on site. However, it cannot substitute for seeing a process with one's own eyes.	Sacks et al. 2009
49.	These functions can support and facilitate participatory decision making by providing more and better information to all involved and by expanding the range of options that can be considered. Of course, they cannot in and of themselves guarantee that senior management will adopt a consensus building approach.	Dehlin and Olofsson 2008
50.	Integration of different companies' logistic and other information systems makes working relationships that extend beyond individual projects worthwhile and desirable.	Not yet available
51.	Use and reuse of design models to set up analysis models (such as energy, acoustics, wind, thermal, etc.) reduce setup time and make it possible to run more varied and more detailed analyses.	Not yet available
52.	Abuse of the ease with which drawings can be generated can lead to more versions of drawings and other information reports than are needed being prepared and printed, unnecessarily increasing drawing inventories.	Not yet available
53.	Automated generation of drawings, especially shop drawings for fabrication (of steel or precast, for example), partly enables review and production to be performed in smaller batches because the information can be provided on demand. Unlike Item 52 above, this and the following item are positive interactions of automated drawing production.	Not yet available
54.	Automated drawing generation improves engineering capacity when compared with 2D drafting, and it is a more reliable technology because it produces properly coordinated drawing sets.	Sacks and Barak 2008; Tekla 2009a
55.	Animations of production or installation sequences can be prepared. These guide workers in how to perform work in specific contexts and are an excellent means for ensuring that standardized procedures are followed, particularly where turnover of workers from stage to stage is high, as is common in construction.	Dehlin and Olofsson 2008
56.	Sharing models among all participants of a project team enhances communication at the design phase even without producing drawings, helping ensure that the requirements are understood and transmitted throughout the team and on to builders and suppliers.	Not yet available

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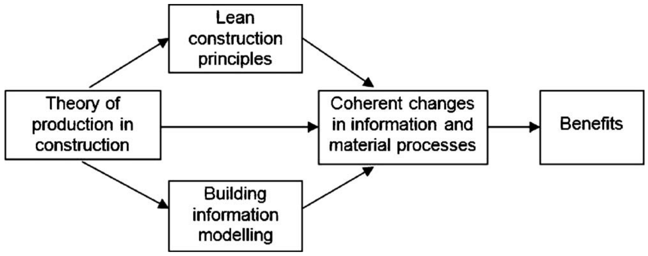

Fig. 1. Dependence of benefit realization through process change in construction on lean construction principles, BIM, and a theoretical understanding of production in construction

tions of lean and BIM. This rigorous framework is expected to be useful for future research (both empirical and design science research) relating to this interaction. In a broader sense, the framework and the analysis can be seen as an exemplar of the interactions between new information technologies and the production systems they serve. As such, it may be useful for research and analysis of such systems beyond the domain of construction.

Methodologically, this is constructive/design science research because it proposes a conceptual framework for analyzing the interaction of two transformative technologies: BIM and lean. Thus, depending on the angle of interest, the primary focus is either on: the influence of an approach to design technology that has a transformative power not only on the design process but on the construction process as a whole, or; on the pull of a transformative approach to management to use this design technology for transcending current constraints for performance.

The 56 issues identified are presented as hypotheses and are intended to guide and stimulate further research. A survey of experimental and practical literature to date shows documented evidence for 48 of the issues. We expect that more of them will be borne out as empirical evidence is gathered, while some may prove to have different effects from those postulated. Nevertheless, the sheer number of the constructive interaction mechanisms identified strongly supports the argument of a significant synergy between BIM and lean.

However, the framework may also be used for understanding the practical issues faced by companies implementing BIM and/or lean. First, the breadth and depth of interconnections between them imply that any company or project on a lean journey should seriously consider using BIM for enhancing the lean outcomes. Conversely, any company or project implementing BIM should ensure that their adoption/change process is contributing to the fullest extent possible to making their processes leaner.

Second, in the current stage of both BIM and lean, it is probable that most companies and professionals are still on a learning curve. The high number of interactions between BIM and lean suggests that perhaps the parallel adoption should be in small steps. It may be a good strategy to carefully define benefits that are desired, accordingly to design and execute manageable BIM/lean experiments, and to proceed in incremental stages toward harnessing even more positive interactions between these two initiatives.

Last, we contend that for comprehensive realization of benefits, changes in information and material processes, BIM tools themselves, and of course lean construction principles should be rooted in conceptual understanding of the theory of production in construction. This issue does not come out of any specific cell or group of cells in the matrix but derives from a holistic view of the situation. As such, this implies that in construction management, a closer interaction between theory and practice, between academia and industry, is needed than has hitherto been the case.

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