A Lean Construction and BIM Interaction Model for the Construction Industry

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An Analytical Network Process (ANP) was created to test the Lean and BIM concepts with data collected from U.S. companies to find the success factors of the Lean/BIM framework. After an extensive literature review, a total of 17 sub-categories for Lean/BIM are classified into three clusters, namely Communication, Production, and Visualization. An ANP network is then established to station the links between the attributes of the framework while computing their importance weights. Eight experienced civil engineers took part in the questionnaire study to assess the relations between the attributes. The main purpose of this study is to reveal the synergy between Lean and BIM with different components reflecting this synergy and present the Lean and BIM synergy on a comprehensive model. The results indicate that Production is the prominent cluster and Production Control, Standardization and Information accuracy are the most important factors in the Lean/BIM synergy. To validate the model, five construction projects were selected to test and observe the results accordingly. The study is expected to help construction industry leaders set their priorities, benefit more from the interaction between Lean and BIM, and revise their strategies accordingly. This study identifies Lean/BIM categories and subcategories as a roadmap for research and implementation. In this context, the study reveals the relationship between the categories/subcategories along with the weights and most and less important categories for Lean/BIM implementation and research.

Keywords: Analytic network process (ANP), Lean construction, BIM, Lean/BIM, Project Management

Introduction

The complexity of construction projects is steadily increasing, whereas the average productivity is not improving at the same pace when compared to other industries. Today, diversity and customer demand are at the focal point for businesses, and the traditional structure of the construction industry is lagging. The Cobb-Douglas production function reveals that the construction industry presents diseconomies of scale; therefore, the productivity becomes even more critical- a 1% increase in the yearly nominal productivity could result in savings up to $100 billion in the construction industry worldwide (Mano et al., 2019) and helps the production function curve withdraw to economies of scale. Moreover, 57% of the time is wasted in the construction industry, where this ratio is only 12% in the manufacturing industry (Aziz and Hafez, 2013). The total cost comparison of the built environment stages indexed to 1$ would be; design (1$), construction (10$), operation and maintenance in 20 years (30-50$) and client's operational costs (salaries, etc.) (400-2000$) (Dave et al., 2013). From this life-cycle point-of-view, creating value and improving business productivity significantly outweigh design-related cost concerns, where design and organizational structure are the key components for overall cost reduction. Design changes, lack of information exchange, poor decision-making, and communication are the major causes of waste in the design phase (Mollasalehi et al. 2016; Olanrewaju and Ogunmakinde, 2020). Also, the traditional nature of labor-intensive production creates coordination issues and competition between teams preventing a sustainable communication atmosphere (Andujar-Montoya et al., 2015). This causes delays in information flows to stakeholders generating bottlenecks and up to 30% rework (Alshawi and Ingirige, 2003; Love and Edwards, 2004; Andujar-Montoya et al., 2020). Gao and Low (2014) mention that unevenness in workload stems from the irregular production schedules or fluctuations in production volumes mainly caused by internal problems such as downtime or missing parts. This is mainly caused by workers or machines working with low capacity. To deal with this, adopting Lean principles might become a potential remedy. BIM supported Lean implementations are even more effective towards coming up with better production schedules.

To overcome such problems, Lean Construction (LC) and Building Information Modelling (BIM) possess a significant potential to revolutionize the traditional project delivery structure and practices in the construction industry. LC is simply defined as "a way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value." (Koskela et al., 2002). Azhar et al. (2015) defines BIM as "a revolutionary development that is quickly reshaping the Architecture-Engineering-Construction (AEC) industry." LC and BIM have been studied mostly separately since the 1990s, but the scarcity in the academic interest on the synergy between the two topics has led to a literature vacancy (Tezel et al., 2020). On the other hand, both concepts have various advantages in terms of performance, quality, and operational improvement. Panteli et al. (2020) implied that BIM is a state of the art in digital design representing one of the most important milestones in Industry 4.0 era. Braglia et al. (2020) developed a Lean metric for identifying construction losses and their underlying causes in Engineer-to-Order construction supply chains. Matthews et al. (2017) revealed that BIM is an effective way of successful asset management, but the lack of BIM knowledge negatively affects everyday practice. They further mentioned that education and learning must be given with special emphasis to incorporate them into BIM implementation strategy so that the construction industry acquire the benefits of BIM implementation. Shou et al. (2020) structured a framework to provide evidence for using Lean to integrate improvement and evaluation in turnaround maintenance project management. Berlak et al. (2020) indicated that digitalization in construction projects result in increased productivity. They further mentioned that BIM is an effective means of simulating the productivity increase. There are certain challenges associated with either implementing Lean and BIM. For example, Adam et al. (2020) evaluated the effectiveness of the Lean training and concluded that not all Lean tools are effective in terms of understandability and transfer. It was further indicated that benefits of Lean management have not yet been understood well by the implementors. Zomer et al. (2021) listed certain challenges related to BIM such as changing work practices, providing education and training, and evaluation of business value of BIM. To build up a capacity for BIM in terms of increasing productivity, efficiency, and quality, Lean concepts are essential to benefit from especially to improve flow reliability and waste estimation (Shou et al., 2014; Mellado and Lou, 2020). Evans et al.'s (2020) study also pointed out to the gap between BIM and LC practices in terms of providing a comprehensive set of steering factors and provided a set of critical success factors with respect to a survey conducted with experts. Mahmood and Abrishami (2020) studied the implementation of BIM in terms of experiencing a reduction in waste and researched the functionalities between BIM and Lean through a survey study. However, the literature still lacks a clear map or structure developed to achieve Lean and BIM integration in terms of enhancing productivity and efficiency.

To fill this gap, this study presents a comprehensive literature review to establish a solid Lean/BIM framework. In this respect, a total of 17 categories were identified from in-depth interviews with industry experts and university professors. Then, the categories were evaluated and tested by using the Analytical Network Process (ANP) to reveal the interrelations and success factors of the framework. The framework also reveals the importance of each category in terms of reflecting the degree of synergy between the Lean and BIM categories. The study is expected to help researchers in further exploring the synergy and interaction categories of Lean and BIM. It is also hoped that the results of the study will raise awareness of the Lean/BIM benefits through a synthesized framework that can be used by industry practitioners to maximize their gains from the combined use of Lean and BIM.

Research Background

Building Information Modeling (BIM)

The technology and process dubbed as Building Information Modelling (BIM) have been gradually developed since the 70s to create, store, analyze, simulate, visualize and manage the geometric and attribute information of an asset through its life-cycle. (Eastman, 1975; Hao, 2012; Li et al., 2017a). The glossary of the BIM Handbook (Eastman et al., 2011: 586) defined 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, planning, construction, and later operation." The concept aims to provide, calculate and edit digital asset data interactively for a more efficient life-cycle management of an asset, which enhances collaboration and streamlines all the processes (Aouad and Arayici, 2010; Hao, 2012). Artefacts, agents, context, processes, and structures are the essence of BIM-based collaboration (Poirier et al., 2016; Papadonikolaki et al., 2019).

BIM has various functions that offer serious advantages for the users aiming to enhance the performance of construction processes. Sacks et al. (2010) mention the functionalities of BIM in various aspects such as visualization of from, rapid design alternative generation, using model data for predictive building performance analysis, and automated generation of documents and drawings. They further imply collaboration and coordination, object-based communication, and direct information transfer as the key aspects of these functionalities. The functionalities offer high concentrations of unique interactions for online communication, multiuser viewing of models, functional evaluation and aesthetic assessment, and visualization of schedules in construction (Sacks et al., 2010). Various other studies also highlighted the benefits of BIM discussing some other key aspects. A combined list compiled from Azhar (2011), Arayici and Coates (2012), and Sun et al. (2017) summarizes the BIM benefits as; (i) automated code checking (Fatt, 2005) and potential for easier share, reuse, and automation of data; (ii) avoiding clashes (up to 10% of the contract amount could be saved) and improved production quality; (iii) faster and more accurate cost, energy and lifecycle analyses; (iv) eliminating the risks of miscalculation; (v) ensuring effective control and sharing of construction documentation; (vi) generating design and construction alternatives ensuring lower life-cycle costs; (vii) improved communication leading to reduced change orders and information requests; (viii) model-based decision making, preventing misinterpretation of design and improving customer service via visualization; (ix) shortening total project schedules (up to 7%); and (x) providing accurate thermal load calculations (Kam et al., 2003) or environmental impact assessment.

Owners and clients realize that the design, construction, and operation of buildings are more efficient and less costly with BIM (Coates et al, 2010). The governments of Finland, Denmark, Norway, and the USA endorsed BIM for public projects (Aouad & Arayici, 2009). The UK government mandated BIM Level 2 directing to develop building information in a collaborative 3D environment with data attached but created in separate discipline models for publicly procured and suitable building projects in the UK in 2016. This requirement will expand to private projects by 2025 (Morrell, 2010; Dave et al., 2013). Today, especially the countries that have access to EU public funds; the UK, Denmark, Netherlands, Norway, and Finland, require BIM for public works (Andújar-Montoya et al., 2019). There is still need for research centers to focus on BIM-related research themes. This way, the construction industry would achieve a strategic advantage by improving the level of knowledge, use, and proficiency of BIM. On the other hand, in some countries like China, economic, law, management, human resources, and technology-related issues are identified as the main barriers before BIM (Hao, 2012, Tan et al., 2019).

Utilizing decision-making information earlier, better early-phase analyses, and reusing information could save up to 15% on new projects, and 35% on repeated projects (Jernigan, 2008). Giel and Issa (2013) concluded from three case studies that a high (from 16% to 1654%) Return on Investment (ROI) is possible through BIM implementation. Azhar et al. (2011) advocated that this range is between 634% to 1633% (Sun et al., 2017). To be able to implement BIM effectively, a bottom-up approach is advised to deal with the resistance to change for BIM (Arayici et al., 2011). But a top-down approach is more widely accepted in the industry due to the traditional production culture. Furthermore, the mindset that views BIM only as a 3D drafting tool hinders achieving the desired outcomes. Without adopting the necessary philosophy, opportunities for the collaboration of teams and using their full analytical capabilities at the BIM implementation are often missed and the design process is not necessarily improved (Al-Hattab and Hanzeh, 2018). Goyal and Gao (2011) underline that the initial investment costs and complexity to adopt BIM (lack of data interoperability/software related issues) are the major implementation challenges for each trade. Sun et al. (2017) added management related issues to the challenges such as lack of management standards, experienced personnel and cooperation capability with partners, inappropriate business models within the fragmented nature of construction leading to changes in workflow, and participants' attitudes toward BIM. Tezel et al. (2020) further contributed to this list for Small and Medium-sized Enterprises (SMEs) by adding time constraints, lack of data on the usefulness of BIM and return on investment, procurement, contract, and standards-related issues, and lack of management commitment and leadership.

Lean Construction (LC)

The concept of Lean Production evolved from the design of the first automatic loom that detects errors and stops operations automatically to avoid defective products by Sakichi Toyoda, the founder of Toyota Industries Corporation (Boakye-Adjei et al., 2014). His son Kiichiro Toyoda, the founder of Toyota Motor Corporation, devised the Just-in-Time (JIT) manufacturing approach after his investigations in the United States (Ko, 2010a). Thereafter, the Toyota Engineer Taichii Ohno and his colleagues gradually introduced the Lean Production system in the 1950s to reduce waste at the shop-floors of car manufacturers and adopted a customer point of performance view (Ohno, 1988; Howell, 1999; Womack, 2007). Then, Target costing (TC), which sets a limit to the cost, has been developed to systematically improve product profitability as responsiveness to consumer demand is one of the main contributors to the profitability (Ballard and Reiser, 2004; Pishdad-Bozorgi et al., 2013). The Lean Production System was embraced as a revolution in manufacturing between 1951 and 1961 (Cooper, 1997). Krafcik (1988) is the first person that introduced the “Lean production” term while he was a member of the research team working on the International Motor Vehicle Programme at the Massachusetts Institute of Technology (Krafcik, 1988; Demirkesen and Bayhan, 2020). Krafcik (1988) confirmed that JIT needs less effort, investment, space, and time (Ko and Chung, 2014).

Lean thinking is comprised of five principles; (i) specify the value and eliminate all non-value adding steps by minimizing variability, (ii) identify the value stream from the perspective of the ultimate customer, (iii) make the value flow without interruption by managing steps with different properties, (iv) let the customer pull, and (v) pursue perfection by kaizen (gradual improvement) and kaikaku (radical change) (Womack and Jones, 2003; Tezel et al., 2020). These principles are supposed to lead organizations to sustainable and effective value creation in the most efficient manner (Shou et al., 2014) by using less of everything (Aziz and Hafez, 2013). Better risk management, greater customer satisfaction and profitability, improved productivity and safety, and reduced project schedules with costs are the major benefits of LC, the reflection of lean thinking on the construction industry (Koskela, 1997; Nesensohn et al., 2014). The interconnections of stages and decisions need to be considered to optimize the whole project rather than working with individual stages (Dave et al., 2013).There are several Lean tools and techniques, which are now being applied in the industries. Among those, the Last Planner System (LPS) provides a collaborative and decentralized planning, control of production, reliable workflow creation and learning from root causes of delays mechanism for project-based industries (Ballard, 2000). JIT is another Lean technique to ensure the delivery of the product at the time desired and in the quantity needed. In this pull system, a downstream process pulls the needed products from the upstream process while the main driver is the customer (Ohno 1988). Visual management (VM) is defined as “the strategy of increasing pervasive information availability, providing people with sensory work aids and consciously removing blockages in the information flows at a work setting” (Tezel et al., 2016). Besides, there are various other Lean tools and techniques such as Value Stream Mapping (VSM), the

A3 method of problem solving, kanban, kaizen, and the 5S. These are implemented to sustain continuous improvement and enhance the performance of processes.

The term Lean Construction was coined at the first conference of the International Group of LC (IGLC) in 1993 (Tezel et al.., 2020). The Lean Construction Institute (LCI) was established by Glenn Ballard and Greg Howell in 1997 to develop and share lean-related project management knowledge. Later, the Lean Project Delivery System (LPDS) was introduced to maximize efficiency through planning, design, and construction (Ballard and Zabelle, 2000). LC is defined as “a way to design production systems to minimize waste of materials, time and effort to generate the maximum possible amount of value” (Koskela et al., 2002: 211).

However, the Lean culture often confronts with the resistance of human-related habits (Bashir et al., 2015). Due to following only contractors’ orders, caring only about their routine and duty, and low education and awareness levels with high mobility undermine the lean integration potential in different parts of the world (Li et al., 2017b). The cultural change necessary for LC within a company is often shouldered by “lean champions” (Pekuri et al., 2012). However, in order to clarify the Lean tools and practices to implement, integration of the Lean culture in the company, considering the market conditions, is necessary (Radnor and Walley, 2008; Lie et al., 2017b). To create a more collaborative atmosphere, company managers need to transform themselves, their practices and business metrics to provide leadership towards building trust, motivation, and competence with the like-minded personnel (Emiliani and Stec, 2005). In SMEs, finance related investment issues, trust-related issues in partnering for LC with larger clients, unawareness of the benefits, skepticism, and lack of client support are the major barriers for lean implementation (Tezel et al., 2018). Integrated Project Delivery (IPD) is a project delivery model that uses common sense of the project team to fully achieve the true potential of the LPDS and supports LC efforts with a procurement/delivery backbone (Sacks et al., 2009a).

Construction is accepted as a complex environment and the value of waste should not be overlooked in complex environments. Exploring the value of waste in construction projects and efforts trying to reduce the waste might jeopardize the workflow (Bertelsen, 2004). There are various applications of Lean that lead to less complex and collaborative processes. Aziz and Hafez (2013) mention that Lean construction projects are generally easier for managing, safer, delivered sooner, and more cost effective as well as being completed with better quality. They further state that Lean based tools might be successfully applied to complex construction projects. Implementing Lean based tools helps to reduce waste and improve process performance (Lapinski et al., 2006). For example, Last Planner system helps define areas for improvement and creates a collaborative environment in problem solving, which in turn leads to reduced complexity. In the study of Salem et al. (2006), a general contractor sought the opportunity to increase human and technical learning with implement ting Lean construction. They tested six Lean construction techniques namely the Last planner, enhanced visualization, first-run studies, huddles meetings. 5S, and fail safe for quality. After a six month of study period, they concluded that each technique created some criteria or changes such as communication, knowledge, team effort, and review work to be done for better performance. In another study, Seth and Dhariwal (2017) studied value stream mapping for Lean and cycle time reduction in complex environments. They concluded that reducing nonvalue adding activities and considering major challenges of complex environments lead to less waste and reduced cycle time. They further implied that value stream mapping is an effective means of process improvement and non-value adding activities reduction.

Lean construction is found to be enhanced when it is synergized with supply chain collaboration. Nowadays, more construction projects are executed with industrialized and standardized production along with the supply chain collaboration to become leaner. When supply chain partners collaborate more, it is possible to smoothen the workflow the construction supply chain resulting in minimized waste and maximized value (Meng, 2019). Núñez-Merino et al. (2020) provided that Lean supply chain management involves organizations that work towards reducing waste and pull what is required to meet the customer expectations. Le et al. (2018) proposed a framework for construction supply chain management implying that Lean and BIM shall be implemented together to control and improve the process flow as well as eliminating waste. They further revealed that construction supply chain management practices require the involvement and cooperation of supply chain participants to increase productivity of construction planning and reduce the risk of non-compliance of supply chain participants. Koskela et al. (2019) investigated construction supply chains from a Lean lens. They concluded that the organizations are linked by the collaborative and integrated processes in terms of the Lean lens, where improvement and supply chain performance control is a joint task. Hence, it is of utmost importance to have early supplier involvement and set long term relationships for strategic collaboration with suppliers.

LC and BIM

LC is a conceptual approach with different tools for project management, and BIM is a tool and process used for efficient information exchange over the project lifecycle. Therefore, BIM needs to be considered to improve and facilitate the leanness concept (Sacks et al., 2010a; Tauriainen et al. 2016; Nascimento et al., 2017; Heigermoser et al., 2019). The team-based approach used in BIM paves the way to the lean-oriented project management, enhancing efficiency and productivity (Brathen, 2015).

Sacks et al. (2010a)'s cornerstone study puts forward the significant synergy between BIM and LC by identifying and comparing 56 interactions, where 52 of them are positive, and eventually showing evidence for 48 of them. According to the study, these intertwined concepts lead to getting quality right the first time to reduce waste. Moreover, improved flow reduces production uncertainty and overall construction time. The visualization capability of BIM helps realize the lean principles of reduction of variability, creating flow and ensuring value for clients.   Furthermore, the study suggested to identify more relations and synergies with new empirical evidence from further studies.

Arayici et al. (2011) advocated that BIM helps reduce waste and is applicable to all project stages, which eventually promotes both lean and green (Ahuja et al., 2017). BIM embraces enhanced information exchange to a larger number of project participants, expediting real-time management (Al-Hattab and Hanzeh, 2015) to complement LC. BIM facilitates leaner construction practices for subcontractors and fabricators with enhanced teamwork, increased prefabrication, better workflow stability, and reduced inventories (Roundtable, 2010). Collaboration in design and construction, participation of end-users, optimization of the whole system are some of the benefits of the LC and BIM integration (Alarcon et al., 2013b; Tauriainen et al., 2016).

Hamdi and Leite (2012) state BIM is beneficial in supporting lean practices like extensive prefabrication, JIT delivery of materials, the LPS, constraint logs, offsite/onsite prefab, push/pull planning, and weekly work planning, resulting in mutual interactions. Implementing BIM and Lean to Supply Chain Management (SCM) enables proactive and periodic reporting, real-time quality checks for stakeholders, and at least

30% of time saved thanks to accurate production and quality data (Dong et al., 2013). Industrialized construction practices contribute to construction planning and control for the LC/BIM interaction (Li et al., 2017a). Ansah et al. (2016) claim that the lean principles reduce project duration by 10%, increase productivity and efficiency by 20% and enhance profitability by 20-40% for Danish contractors, which can be further improved with the implementation of BIM. Te Sutter Health's Castro Valley project in California implemented LC/BIM and experienced a decrease in rework by 15% and the project is completed on budget and six weeks earlier than anticipated (Dave et al., 2013). Ghosh et al. (2014) reported substantial improvements comparing two phases of a healthcare project with reduced work hours, overtime, and rework through the LC/BIM collaboration. According to the authors, the BIM model, commitment tracking, IPD and pull planning reduced material waste by 6% , and more than 7.5 metric tons of CO2 equivalent per short ton of drywall (MTCO2E) of greenhouse gases (GHG) emissions in the drywall manufacturing and transportation. The design and construction of the first phase of the Istanbul Grand Airport (IGA) project, which is one of the largest in the world, achieved successful management performance measures with the Lean/BIM collaboration (Koseoglu et al., 2018; Andújar-Montoya et al., 2019).

Lack of Virtual Design and Construction (VDC) guidelines, training, commitment, interoperability, client request, and cultural barriers, contractual and legal aspects, software/hardware issues are the obstacles in the literature for the LC/BIM synergy (Alarcon et al., 2013b). Traditional procurement routes and forms hinder coordination, cooperation, and innovation to foster teamwork in the Lean/BIM implementation (Howell, 2005; Dave et al., 2013). Therefore, new forms of contracts such as Alliancing, ConsensusDocs and IPD / IFOA (Integrated Form of Agreements) present the needed flexibility to realize the potential of team members for LC/BIM throughout the project life cycle (Dave et al., 2013).

To teach and explain the BIM/LC integration, different methods are adopted in the literature. Li et al. (2018b) use Lego sets and hands-on experience in a role-play simulation game to teach the process of prefabrication housing production (PHP) to students and practitioners by integrating the LC principles with a RFID-enabled BIM platform (RBIMP). An advanced simulation game of RBL-PHP is found more effective in the learning process for students rather than the traditional multimedia presentations. Moreover, according to the authors, PRB-PHP improves the plan percent complete (PPC) by 8.11%, reduces extra costs by 80.12%, improves productivity in the manufacturing process by 50%. Dallasega et al. (2020) used the Villego simulation to teach BIM, Virtual Reality (VR) and Augmented Reality (AR) to support LC, improving the Key Performance Indicators (KPIs) for construction time, level of quality, and waste elimination.

What motivates the adoption of Lean and BIM is that the construction industry needs waste elimination (Babalola et al., 2019). The construction industry is generating a considerable amount of waste such as safety breaches, lack of proper time management, lack of visual display, unnecessary movement, lack of coordination, and collaborative planning. At this point, Lean both as a philosophy and a way of practical thinking supports processes in BIM such as enhanced visual display, improved communication and collaboration, and better visual display leading to enhanced safety. BIM also supports Lean in terms of automating non-value-adding activities, providing better visualization and workflow. There are also innovative efforts in the construction industry such as transforming into Industry 4.0, which has recently been articulated as Construction 4.0. Even though BIM is considered as a milestone for Construction 4.0, there are still problems with adopting the Industry 4.0 implementations (Gerges et al., 2017; Demirkesen and Tezel, 2021). The major barrier has been mentioned as 'resistance to change' in several studies (Osunsami et al. 2018; Bademosi and Issa, 2021, Demirkesen and Tezel, 2021). Digital twin (DT), which is defined as a “digital equivalent to a physical product’’ by Grieves (2019), is another transformation opportunity for the construction industry. However, the construction industry is still challenging with modernization and advancement in technologies compared to other industries. One other concern is that little impact of DT has been observed in the construction industry so far (Opoku et al. 2021).

Lean construction is rather adopted to reduce waste and change mindset with its principles of 'respect for people', 'continuous improvement', and 'no blame culture'. The industry is now applying Lean tools and techniques in several projects. However, BIM alone have still certain challenges such as lack of information accuracy, collaboration issues, communication gaps, and ambiguity of requirements (Terreno et al., 2019). Similarly, Lean construction alone is not sufficienct to achieve Lean goals such as waste elimination and increased value (Moghadam, 2014). The in-depth analysis of previous studies indicated that when integrated Lean and BIM result in better outcomes. Ahuja et al. (2018) implied that organizations embracing an integrated approach in terms of BIM usage with associating it with Lean and green initiatives experience improved project outcomes. In another study, Koseoglu and Nurtan-Gunes (2018) implemented mobile BIM delivery of project information via tablets in a complex airport project. They reported that using technology enabled BIM practices along with Lean construction principles resulted in improved project management processes and successfully achieved Lean principles. This also contributed to the proper identification of bottlenecks. Bygballe et al. (2018) studied the use of Lean principles and BIM in a public construction project in Norway. For this project, whiteboards and a so-called BIM kiosk was used to display the takt plan-a Lean technique-to facilitate the transparency at all levels of the project. They highlighted that this is driven by a culture of openness and transparency, where learning becomes possible.

Given this background, it is apparent that Lean and BIM integration provides value to the organization as well as helping to overcome resistance to change. In that sense, Lean and BIM structured organizations are more likely to innovate. This study focuses on the U.S. construction industry considering its global share and experience in the international market. According to the data provided by the U.S. Bureau of the Census (2018), total construction spending in 2018 was reported as 1,308 billion, 998 billion was from the private construction. This large amount of spending is an indication of U.S. construction industry might be considered as an estimation tool for evaluating overall economic performance and economic growth (El-Adaway et al., 2020). On the other hand, Danforth et al. (2017) implied that lack of organizational learning in the U.S. construction companies leads the industry to consider economic recessions as threats even though several innovation opportunities might arise during these recessions. A recent study conducted by Calderon-Hernandez and Brioso (2018) reported that construction projects suffer from long decision-making times for the design phase, exhausting processes for understanding the documents in the planning stage, and lack of real time monitoring of the project with the automized tools. On the other hand, Murguia et al. (2016) mentioned that implementing LPS improves the performance of the production system, which is implemented during the finishing phase of a residential building. Priven and Sacks (2016) studied eight residential construction projects and concluded that LPS is even more effective when applied with social subcontract, which resulted in enhanced coordination and collaboration. Schimanski et al. (2021) further implied that combined use of Lean construction methods is an effective way to standardize BIM models and foster the systematic use in construction execution. The study conducted by Hall et al. (2019) investigated firms operating in

Silicon Valley in terms of their strategies to enable digital manufacturing. DPR, a large construction company in the U.S., reported that they coordinate their off-site work using advanced BIM capabilities. This way, they mentioned that they gain important knowledge regarding tolerance, logistics, and design requirements for digital manufacturing. DPR is also one of the construction companies actively implementing Lean in many projects and report the benefits gained through this implementation. This was expressed by the company to provide opportunities for learning and leverage the relational approach.

Considering the industry characteristics and creating opportunities for learning in organizations, it is essential that companies must benefit from the advancement in the technology along with the novel approaches/methods. Among those, as evidenced in several studies, Lean and BIM synergy might provide extensive benefits as well as increasing team learning, collaboration, and cooperation. However, the companies are still not provided with a complete guide how to best benefit from this integration. Especially, there is a growing need for the residential construction projects, where Lean implementations along with the automized systems have been tested over the recent years to improve time and cost management. The motivation of this work comes from the need for (1) the integrative methods, promoting (2) innovative techniques, and providing empirical evidence regarding the (3) benefits of integrative methods. These points are often assessed as the gap in the literature since the benefits of using integrative techniques have not yet been understood by the industry practitioners due to lack of comprehensive guidelines and cornerstone studies. Therefore, this study presents a Lean and BIM interaction model for the residential construction projects encompassing novel parameters to guide industry practitioners and policy makers revise and revisit their strategies accordingly.

Categories

In this study, a total of 5 categories and 28 subcategories were identified to explore the synergy between LC and BIM after the first round of literature research. However, after an in-depth literature review and taking expert opinions from industry practitioners and academics studying the Lean/BIM interaction, some categories and subcategories were merged into one category and the irrelevant ones were eliminated. For example, planning and scheduling in BIM and JIT Delivery categories are merged into one subcategory, or morning huddles are integrated into Model Construction because of the literature compatibility. Separated LC (Takt-Time, Kanban) and BIM (Level of Detail) terms are categorized according to the affinity. Communication (C), Production (P) and Visualization (V) categories are selected to maintain comprehensiveness and simplicity. The final list is comprised of 3 categories and 17 subcategories, reflecting the interrelations between LC and BIM.

Collaboration in design (C1)

Design of construction projects requires efficient collaboration between different professions. The efficiency of the whole construction process depends on the early stages of design (Boothroyd et al., 1994). Late discovery of errors and omissions in the design lead to rework, schedule delays, and scope changes that constitute roughly one-third of the contract value (Love et al., 2014). Design costs are marginal compared to the project life-cycle costs and any improvement in the design can reduce the life-cycle costs significantly. Andi and Minato (2004) highlighted that errors stem mainly from the human factor in the design process. Highly integrated project delivery is often stimulated in LC where design charrettes (a short and collaborative meeting), Big Room (a space where project teams are co-located or share with many visual information and artefacts) or knot working (designer meetings at planned or spontaneous critical points) meetings are encouraged to consider all options in terms of design error management with the use of the whole team's loaf in the same location (Love et al., 2011; Eastman et al., 2011; Alarcon et al., 2013a). Tauriainen et al. (2016) determined that 12 out of 18 problems such as acquiring input data, collaboration among designers, and modeling instructions could be solved by Big Room meetings in Lean/BIM coordination at the design phase. Al-Hattab and Hanzeh (2015) advise to use root cause analysis to reach the main cause and a smoother resolution of errors in these meetings. According to their social network theory approach, Lean/BIM-based projects create a more cohesive atmosphere and upgrade information flow, preventing information deficiencies among teams. Moreover, BIM improves assembly optimization to implement LC. Ahuja et al. (2017) observed that BIM-based MEP system modeling contributes to both green and lean outcomes. Lu et al. (2017) emphasized the superior role of BIM in the design-related collaboration and communication in green buildings. BIM also enables 3D visualization, animated scheduling, clash detection, environmental analyses, automated quantity take-offs, etc. that heavily influence the design phase of construction (Akinade et al., 2015, Mahamadu et al., 2017; Gbadamosi et al., 2018) to establish flow and to eliminate planning and process variabilities (Aslam et al., 2020). This way, the efficient capture and flow down of the design intent lead to increased iteration for value improvement and predictability of investment costs (Dave et al., 2013). Al-Hattab and Hanzeh (2018) found that only some members of the design team such as the project manager and architecture group leaders are the hubs of the social network, where others work solely on their computers and conduct calls only when conflicts arise. This shows that a more distributed density in the communication could be achieved by implementing the highly collaborative BIM environments.

BIM facilitates the procedures for collaborative design domains. As a result, it allows collective teamwork through virtual capabilities to co-locate teams and solving conflicts swiftly and concurrently (Scherer and Schapke, 2011). The internal (multiple users within an organization simultaneously edit the same model) or external (multiple designers simultaneously view or separate multi-discipline models) models are used to prevent collisions in design (Sacks et al., 2009a). However, if data sharing protocols are not adequately designed; attribute, location, object, allocation of updated information, scope, simultaneous editing, and task-related issues occur (Dave et al., 2013). Tender documents and contract engagements as well as project design need sufficient time to ethically embody the production process (Mhando et al., 2018) as the synergy between LC and BIM could only be fully exploited through multi-level considerations (Sacks et al., 2010a).

Coordination and Collaboration among teams (C2)

The fragmented nature of construction is highly dependent on the information exchange between stakeholders working in different locations (Arayici and Coates, 2012). Teamwork and team performance could be improved by the implementation of LC (Castillo et al., 2015; Lööw, 2019; Zegarra and Alarcon, 2019). It is a fact that coordinating team meetings is a costly effort due to a large number of project participants' involvement (Mehrbod et al., 2015, 2019). However, as the Toyota Production System promotes, a wider knowledge base to select the most suitable option could be achieved by extending the number of decision-makers and options (Liker, 2003; Sacks et al., 2009a). Selecting the right people and the contract strategy in the early stages is an essential part of the LPDS (Zimina et al., 2012; Alarcon et al., 2013a). The partnership networks should be extended to improve the culture of working for one project (alliancing) or longer terms (Sacks et al., 2009a). Transparency is achieved by discussing the design and implementation processes, and the BIM model, mutual understanding of goals, risks, limitations, specifications, work drawings to improve the reliability of projects (Haar and Drevland, 2016; Vaidyanathan et al., 2016; Matthews et al., 2018). For a more predictable end-product, learning from stakeholders' mistakes, developing trust, and long-term relationships are encouraged in BIM-oriented projects (Mahmood and Abrishami, 2020). According to Papadonikolaki et al. (2019), to be able to reinvent the collaboration in BIM, teams need integration and collaboration through innovation in the project strategy and thinking beyond the tools. Countries like China started to incentivize the use of BIM tools, Total Quality Management, the Last Planner System, and visual management to realize lean management while forbidding excessive layers of sub-contracts that efface the outcomes by separation of interests (Hao, 2012). Dave et al. (2014) propose a system to improve the communication flow that uses the lean principle of one-piece flow and addresses both explicit and descriptive information. This way, meeting new customer needs becomes easier with an appropriate messaging interface protocol.

Last Planner System Implementation (Safety, Fail-Safe in Lean-Real time access in BIM) (C3)

Production systems are categorized as push and pull systems (Huang and Kusiak 1998). LC aims to adapt the whole construction process to the pull system. Plans and schedules are traditionally push systems in the construction industry. However, the look-ahead procedure in the Last Planner System (LPS) allows pull scheduling (Ballard, 2000; Sacks et al., 2009a).The LPS is a construction production control and planning system aimed to reduce the workflow uncertainty and transfer of error in between activities. In 1992, Glenn Ballard started to develop the LPS and his Ph.D. thesis from the University of Birmingham is the complete guide to it (Ballard, 2000a; Heigermoser et al. 2019). In the LPS, the systematical identification of equipment, information, materials, and labor is tuned with the flow of work (Hamzeh et al., 2015; Bartolini et al., 2019).

An initial meeting to establish milestones and deadlines from the Master Schedule (including the entire project duration) is followed by the Look Ahead Planning (Ballard, 2000; Ballard and Howell, 2003). The look-ahead planning depends on Percent Plan Complete (PPC) measurements (Abdelhamid et al., 2002), the percentage of the activities actually completed versus planned in a week time, and aggregated or synchronized systems (Dave et al., 2014). This phase identifies workflows, usually 6 weeks in advance, to bridge the long and short-term work programmes (Tommelein and Ballard, 1997). After developing a plan for the constraints affecting the start of activities, the constraints are categorized and disposed of before the activities actually start. Then, a weekly schedule (or commitment plan) is completed to show the highest level of detail. This schedule should regulate the definition, soundness, sequence, and size of the activities (Andújar-Montoya et al., 2019; Heigermoser et al. 2019). Weekly meetings create a sharing culture between stakeholders with PPC measurements representing the efficacy of the LPS process (Ballard 2000; Kim et al. 2015). Reason for Non-Completion (NRC) must be provided if the PPC is not satisfactory by the foreman involved for root cause analyses and future actions (Dallasega et al., 2020). These processes ensure better sequencing and certainty for a smooth workflow (Goyal and Gao, 2011). Moreover, Daily Huddle Meetings (DHM) (a short, daily meeting to review a day's work and share opinions) allow team members to share their work development/plans and help reduce the number of accidents caused by the lack of safety awareness resulting in fewer number of accidents in the field (Enshassi et al.,2019).

The LPS also helps generate an integrated design, and increased resolution of project planning and control with BIM (Dave et al., 2013). 3D geometric models and communication in BIM could facilitate the flow visualization of work processes for the LPS (Sacks et al., 2009b; Li et al., 2018b). Off-site production or prefabrication is encouraged in the LPS as these practices have minimum error tolerance (Goyal and Gao, 2011). Vaidyanathan et al.'s (2016) study combining the LPS with the location-based management system (LBMS) reduced the slab pouring cycle time by 50% on average and increased the labor productivity. After some interviews with different designers and managers from three case studies, Tauriainen et al. (2016) found that the LPS facilitates acquiring the required data from different disciplines on time, collaboration, and coordination between designers, raising awareness of the modeling scope and real conditions and removing the excuse of time lag. Ansah et al. (2016) advocated that the LPS would increase worker involvement and satisfaction with a sense of growth and self-esteem. The KanBIM concept, which is a workflow management/information system, was developed by Sacks et al. (2010, 2013) and further improved by Gurevich and Sacks (2014) to support negotiation and decision making on a daily status. It also allows the combined functioning of the kanban and LPS through BIM models. Sriprasert and Dawood (2003) developed the Lean Enterprise Web-based Information System (LEWIS) to facilitate multi-users for collaboration. Dave et al. (2011) developed VisiLean to support the implementation of the LPS workflows on BIM. Recently, Heigermoser et al. (2019) presented a BIM-based LPS tool that can integrate the LPS with the 4D BIM processes. Figure 1 presents the stages of the LPS.

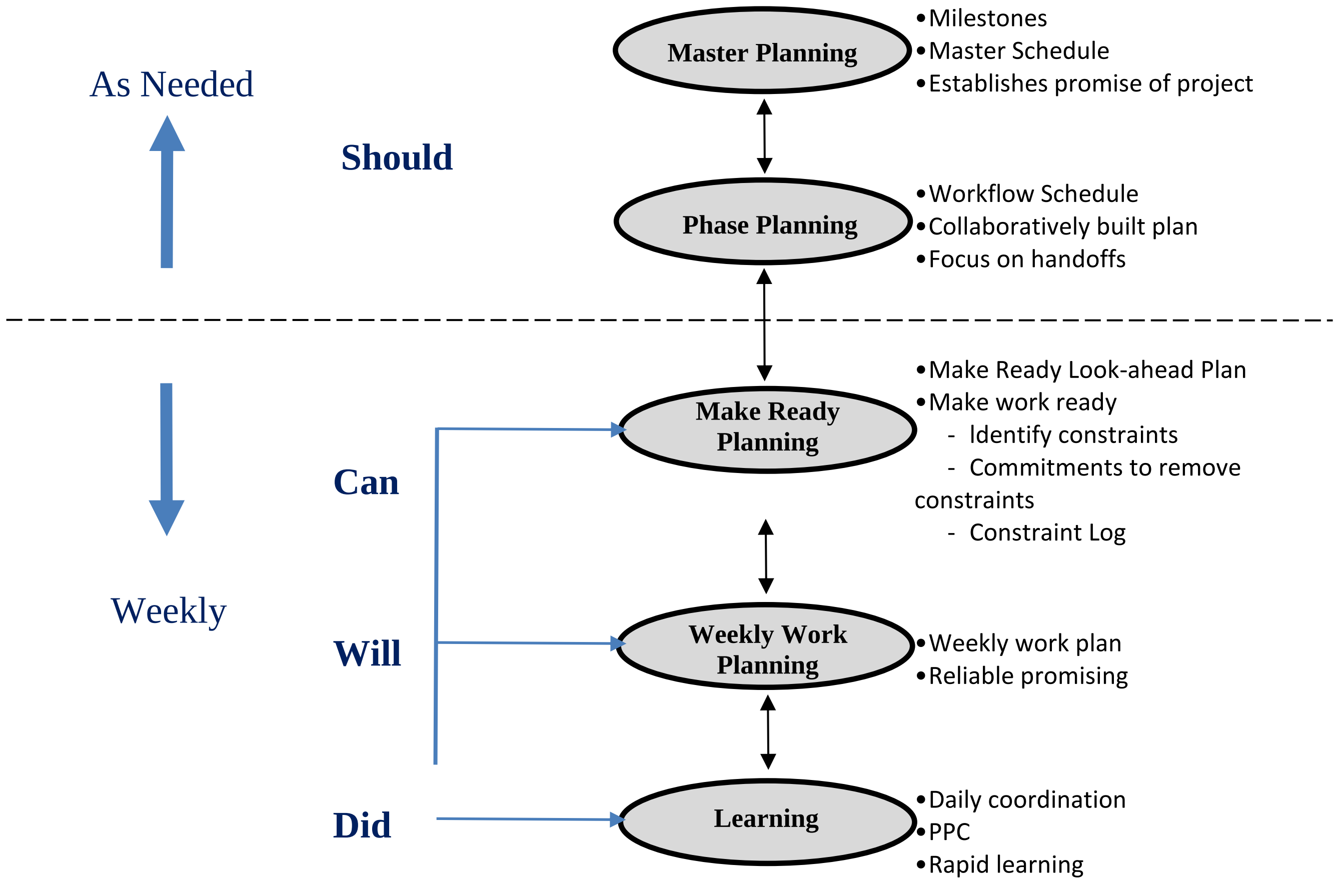

Figure 1. Last Planner System stages (Adapted from Ballard and Tommelein, 2016).

Object-based communication (C4)

In the Lean/BIM integration, sophisticated systems such as the prototype of KanBIM, LEWIS, and VisiLean have been developed to integrate product and process information. The object-oriented characteristic of BIM can be used for prefabrication, constructability, quality and time of construction, economy, and safety to take advantage of the transparency and automatic flow of information (Nawari, 2012). As technology develops, new tools are combined to achieve leanness. Radiofrequency identification (RFID) and Global Positioning System (GPS), and the Internet of Things (IoT) are essential tools to utilize for constant traceability and work assessment (Li et al., 2018a). Dave et al. (2016) developed a system with IoT components to track the elements of the worksite. This way, LC practices merged with IoT components to facilitate logistic operations (Li et al., 2018b). The IoT is used for collaboration and coordination, facility management, health and safety management, logistics, operations, and monitoring (Tang et al., 2019). However, the data received from these technologies needs to be data-mined; real-case studies should be conducted (Tezel and Aziz, 2017); effectiveness of communication, investment rate of return, training and technical risks should be assessed (Ikonen et al., 2013; Niu et al., 2016); and full BIM models are necessary to employ these technologies in PHP (Tang et al., 2019). Object-based communication can effectively support the Lean/BIM integration process with developing technology.

Continuous Improvement (P1)

"Kaizen" is the Japanese term for continuous or incremental improvement, defined by a four-step "Plan-Do-Check-Act" process similar to the Deming cycle originated from Shewhart's (1931) scientific experimentation method (Sacks et al., 2009a; Heigermoser et al., 2019). The data storage and sharing ability of BIM enables learning from past projects to improve the practices in future projects. To do this, work streamlining opportunities for waste reduction (cost, time, and rework) should be investigated from past records. Additionally, Muda Walks (going to and observe the work area to identify potential improvement opportunities) are useful in identifying wastes through the observation of operations and in seeking improvement opportunities (Ansah et al., 2016). The kaizen mentality reduces variability and uses relevant technology to increase the efficiency of processes and people (Womack and Jones, 2003; Pekuri et al., 2012). Construction and demolition waste can be constantly reduced within the Lean/BIM synergy through design reviews, better site utilization, and automation (Chang et al., 2015). Moreover, pre-task hazard analysis may dramatically eliminate safety hazards while the kaizen mentality reduces accidents with constant root cause analyses (Enshassi et al., 2019).

Flexibility (P2)

In the construction industry, production is constrained with parameters like technology, local resources, legislations, and natural environment (Hao, 2012). In this restricted atmosphere, projects are constantly changing by those parameters that demand flexibility in technologies, teams, machinery/plant, and materials. The Lean/BIM interaction can facilitate construction products to be produced similar to industrialized products with the right planning and organization. Improved control of spatial tolerances is convenient with the analysis of 3D models (Taguchi 1993); therefore, BIM is an advancement in visualization with its different levels of detail. Including manufacturing-like techniques such as prefabrication may reduce the variability in and improve the flexibility of projects. Moreover, higher precision tolerances would reduce variability and waste to help achieve the target values (Sacks et al., 2010a). With the help of a bottom-up Lean/BIM approach, people's understanding and skills are improved to successfully apply the change management strategies that eliminate the resistance to change (Arayici et al., 2011).

Information accuracy (P3)

The dynamic nature of design and construction needs smooth information flows to cope with waste. Due to misleading or outdated drawings (Love et al., 2000; Ashford, 2002), distractions from the work at hand with long waiting intervals between responses to information requests cause extended project durations and growing financing costs (Ballard, 1998). Information flows are characterized today by the advancements in IT that enable stable information flows with frequent transactions. Tribelsky and Sacks (2011) affirm that IT helps improve access to information, budget and cost control, collaboration, cycle times, monitoring/control, procurement, quality of design documents, and management of design changes in projects. The extra work done due to low technical compatibility for an accurate information exchange is often referred to as technical interoperability (Poirier et al., 2014; Brathen, 2015). At this point, BIM can facilitate 3D models, building product specifications in the design phase, performing clash detection and energy analysis, management of change orders, performance tracking, simulation and testing of different alternatives, which improve the information accuracy (Alarcon et al., 2013b; Tauriainen et al., 2016). These tools allow for a more accurate financial and budgetary assessment (BIM 5D) for both the owner and client

(O'Loingsigh et al., 2014). However, coordination and screen casting regulations need to be transparently set (Mehrbod et al., 2019). Integrating BIM into a project early on cloud platforms may help regulate the project information from different disciplines and reduce the ambiguity (Doumbouya et al., 2016).

The accurate and dynamic planning abilities of BIM are especially useful for LC approaches such as JIT delivery and Value Stream Mapping (Li et al., 2017a). At the construction phase, the Lean/BIM integration reduces rework and improves flow, safety, productivity, and quality (Dave et al., 2013). In the operation and maintenance phase, administrative, managerial, and technical actions are intended to keep the building performing the required functions (Komonen 2002; Shou et al., 2014). Without accurate project information, facility management strategies would be unsatisfactory and as the project size increases, the financial loss due to this becomes colossal. To prevent such situation, stored BIM files and Lean thinking create an environment for comprehensive analyses and could be used for better maintenance performance (Shou et al., 2014). Shou et al. (2014) combined BIM for assessment, inspection, modeling, and repair, and Lean to increase transparency, reduce variability and wastes, improving the efficiency of maintenance processes.

Improved planning and scheduling in BIM with JIT Delivery (P4)

According to the LCI (2013), pull planning requires backward working from a target completion date on defined and sequenced tasks of which their completion releases work. Pull planning is a make ready technique that eventually improves the definition of tasks (Ballard, 1999). An appropriate critical-path-method master schedule in conjunction with milestone-based short-interval planning helps increase the efficiency and achieve more predictable results (Ghosh et al., 2014). JIT delivery is a lean tool that aims to reduce material storage (inventory) and overproduction on-site by sequencing the procurement and work at hand. The pull-driven structure of LC aims to minimize buffers and inventories (Wu and Low 2012) and helps reduce the accidents caused by improper use of tools (Enshassi et al., 2019). Minimizing the response times from suppliers to end-users could be achieved by minimizing production flow times. Therefore, JIT is used to eliminate the wastes in processes (Ansah et al., 2016).

Panelized construction applications, which need integrative methods to combine manufacturing and assembly, are becoming more common in the construction industry (Handan et al., 2015). Automated fabrication practices help eliminate human errors and facilitate a smooth production flow (Alarcon et al., 2013b). Moghadam et al. (2012) integrated a Lean/BIM model for modular construction using Value Stream Mapping. The model resulted in reduced wastes, time, and resource usage. Irizarry et al. (2013) paired BIM with GIS to track and monitor the materials and inventories in a construction project. This way, schedules and cash flows are dynamically visualized (Alarcon et al., 2013b), streamlined and the communication with the supply chain is handled better (Hamdan et al., 2015). An optimized schedule from the integrated BIM model data with the JIT thinking and productivity rate of crews could enable predicting different scenarios to minimize costs (Lu et al., 2016).

Production Control (P5)

The continuous learning principle of LC aims to reduce defects and deviations as much as possible with constant communication, automated code checking, and design charrettes (Al-Hattab and Hanzeh, 2015). For example, the process diagram can track progression step for each process in a construction operation as well as recording flow in units, sections, and departments. The problems faced in production might be tracked through check sheets also known as defect concentration diagrams to collect data on the frequency of defects, causes, events, and patterns of problems (Ansah et al., 2016). The PPC used in the LPS can help compare actual vs. planned work. This analysis could predict future risks. Ghosh et al. (2014) used the LC principles and tracked, monitored, and optimized the steps used for production with the LPS. At construction sites, defects may occur due to a lack of inspection on work procedures. To solve this issue, Park et al. (2013) developed two automatic field inspection methods using augmented reality and image capturing technology for a specific time interval. Such applications utilizing new technologies are becoming more widespread.

Maturity level is a crucial factor to merge lean practices into BIM tools. In BIM implemented projects, often a group of “BIM experts” is needed to control and shape the model. Therefore, relevant training and expertise are needed to utilize the technology. Moreover, the level of model details used in projects and coordination responsiveness may differ in different zones (Sacks et al., 2010a; Hamdi and Leite, 2012). Hence, ensuring a certain level of maturity is not only essential for BIM but also critical for LC practices. However, there are certain challenges for achieving such level of maturity. For example, lack of training has been frequently mentioned in previous studies as a major barrier for Lean in the construction industry (Wandahl, 2014; Demirkesen and Bayhan, 2020).

One of the main benefits of BIM is clash detection between the building systems, enhancing production control and resolving conflicts (Sullivan, 2007; Goyal and Gao, 2011). This minimizes rework as defects are accounted for 3.15-4% of the contract value in residential construction (Mills et al., 2009; Love and Li, 2000; Park et al., 2013). A BIM-based design resolved over 2.4 million clashes on a hospital project (Khonzade, 2010), inferentially contributing to over $1 billion in cost savings (Wang et al., 2016, Mehrbod et al., 2019).

Reducing Variability (P6)

Shewhart (1931) identified reducing the variability on significant product characteristics as the target in statistical quality theory. Hopp and Spearman (1996) aimed to reduce the temporal variability in production flows in queuing theory (Sacks et al., 2009a). Similarly, lean focuses on reducing the variability in product, production processes and production cycle durations. The lean construction principles aim to reduce these three elements and enhance continuous improvement (Sacks et al., 2010a). The application of BIM can facilitate resource arrangement (i.e. material, crew, equipment) to align with the schedule. The performance modeling of an organization helps make provisions against variability (Alarcon et al., 2013b). For instance, in the study by Ghosh (2014), putting a stricter tolerance limit (one third) to the electrical systems' modeling resulted in a significant reduction of rework, material waste, and labor hours. PHP contributes to the variability reduction by quality control in a controlled environment and mitigation of limited construction space and buffers (Jaillon and Poon, 2010; Li et al., 2018b). However, beyond a smooth logistics flow, logistic operations are considered as non-value-adding in Lean (Bartolini et al., 2019), which should be minimized. According to Mahmood and Abrishami's (2020) questionnaire, maintaining information integrity and 4D model-based scheduling show a high positive correlation with the reduction of variability in LC.

Process Standardization (P7)

Inefficiency as a barrier for successful completion of projects is frequently mentioned in previous research for the construction industry. The traditional construction culture and slow adaptation to changes due to the fragmented structure fail to foster innovations. However, Lean thinking guides the industry to eliminate non-value-adding activities and waste (Arayici and Coates, 2012). Standardization, as a Lean principle, should be considered as a long-term goal (e.g. using a standard file type - IFC) that eliminates issues such as starting from scratch and difficulties in executing multiple tasks leading to waste (Nekoufar, 2011; Hamdi and Leite, 2012). A meticulous approach to standardization not only defines the actual condition with a systematic language but also enhances predictability and increases efficiency with continuous improvement (Morgan and Liker, 2006; Pekuri et al., 2012). BIM enables accurate data to be captured for reuse and improvement of successive projects (Alarcon et al., 2013b). Process improvement is possible with the measurement of standardized and documented past performance (Sacks et al., 2010). In this respect, a SCM system can be implemented to improve transparency, quality control, proper tracking, and monitoring (Dong et al., 2013). On the other hand, excessive standardization and controlling mechanisms may hinder the flow. Hence, standardization needs to be carefully addressed to achieve higher performance.

Systems Design for Flow and Value (P8)

The traditional production management neglects the criticalness of transportation without using advanced flow and value (Koskela, 2000). Before establishing a system with flow, project managers should ensure the flow of communication systems. In the construction industry, the flow is associated with the waste control in materials, prerequisite tasks, information, equipment, and people (Aziz and Hafez, 2013). Hence, it is essential to manage the flow by managing the resources in an efficient manner to sustain continuous improvement. Tauriainen et al. (2016) reported that insufficient collaboration between designers, late input of data, and long response time exhaust the nature of provisions for the Lean/BIM implementation. According to Al-Hattab and Hamzeh (2018), changes in the traditional mindset and collaboration are two fundamentals to create flow with BIM. The visual models of computer-simulated buildings and temporary objects with planning and supply information can facilitate a reliable workflow. BIM enhances the flow with clash detection, detailed shop drawings, and 4D planning. A BIM 4D model for a prefabricated building system reduced the work-in-progress by 61%, man-hours spent in transportation by 38%, and average walking distance for each assembler by 88% (Bortolini et al., 2019). To reduce cycle times, total construction duration, phase of construction, and flow of materials and tasks should be managed (Koskela, 2000; Sacks et al., 2009a). A single piece flow that conceptualizes products as batches is benignant (Sacks and Godin, 2007). Concurrent engineering practices that optimize engineering cycles with tasks conducted in parallel by multi-disciplinary teams can enhance flow and value (Sacks et al., 2009a, 2009b; Ansah et al., 2016). Moreover, coordination and model-based communication through BIM with the LPS improve the feasibility of plans and workable backlogs (Goyal and Gao, 2011), where the look-ahead planning supports the pull process (Hamdi and Leite, 2012). In this regard, the KanBIM based on the LPS enables the visualization of a product and process flow that helps continuous improvement (Sacks et al., 2010b; Moghadam et al., 2012).

Target value design (P9)

Target value design (TVD) is a Lean strategy to manage product profitability by setting a target cost. The target cost is set considering the desired profit margin and expected revenues (Ballard and Morris, 2010). LC aims to eliminate wastes to reveal the true value of works because Lean prioritizes the ultimate customer value. Choosing the right tool for a specific problem shows maturity in LC that could provide value (Nesensohn et al., 2014). TVD is also an effective method for IPD by creating a communication channel among various stakeholders to best manage a project (Jung et al., 2012). IPD enables the project team to establish target values collaboratively. This mutual agreement results in an increased ownership and likelihood for achieving those targets (Pishdad-Bozorgi et al., 2013). At this target establishment phase, different design options and predictive analysis with BIM help the team establish the target value. From a life-cycle point of view, the facility manager should be a part of the IPD group to represent value from the client’s perspective. The as-built BIM model should include a detailed cost breakdown to help determine a target cost for subsequent projects (Pishdad-Bozorgi et al., 2013). Target value design (TDV) constrains the design and construction of a facility to a maximum cost (Zimina et al., 2012). This way the initial scope is completed for as much as 19% below the market cost (Dave et al., 2013; Tauriainen et al., 2016). Especially complex and integrated projects, such as healthcare project, could benefit from the Lean/BIM integration in this regard for their building systems for specified medical equipment, room size, differentiated indoor environment quality measures and so on (Barista, 2007; Enache-Pommer et al., 2010).

Designing out Errors (V1)

A smooth construction process without waste is one of the main promises of LC. According to a study conducted over four years, Computer Advanced Visualization Tools (CAVT), tools for providing ability to visualize product and process models in the design and construction planning processes, were found enabling waste reduction and improved workflow to enhance customer value (Rischmoller et al., 2006; Sacks et al., 2009a). This indicates a strong synergy with LC (Alarcon et al., 2013b). BIM enables responsive design according to the clients' value perception and testing different design solutions (O'Loingsigh et al., 2014).Clash detection is a major BIM function where architectural, structural and MEP models are aligned with each other to check soft and hard clashes. The Navisworks, Solibri Model Checker, Tekla BIMSight software are used in the market to conduct automatic, geometry-based clash detection. A hard clash is the occupancy of the same space by different objects and a soft clash is an insufficient access to a space because of the closeness of objects (Dave et al., 2013).Hamdi and Leite (2012) asserted that experience and skills are key factors for a successful clash detection process.. In this respect, insufficiently simple tools fail to function at the right level of customizability, where too complex tools can diminish the productivity of teams requiring more time to adapt and correct mistakes (Dong et al., 2013).

Graphical information - Visual cues in Lean (Visual management) - Visualization in BIM for better representation of the design model (V2)

Construction projects are becoming increasingly complex. One of the main functions of BIM is to visualize project information and integrate projects that are versatile and detailed. At these projects, different professions need to work in harmony to achieve the project goals. Ansah et al. (2016:788) identified Visual Management (VM) as "an information communication technique to increase efficiency and clarity in processes through the use of visual signals". Therefore, VM is used to predict and control projects. The study of Khonzade et al. (2006) confirmed that implementing CAVT and Virtual Design and Construction (VDC) enhances Lean project delivery

(Sacks et al., 2009a). In Sutter Health's LC delivery process, VDC was implemented to interact between the design and construction with 3D models that resulted in zero change orders, nearly 6 months earlier completion, and $3 million in avoided costs (Gilligan and Kunz, 2007). In BIM, instead of using 2D drawings, the 3D visual representation of systems and structural details developing according to the project plans (4D BIM) enable a deeper understanding of the construction process for the project team (Dave et al., 2013).BIM also allows in-house generation of 3D renders and provides a better visualization with less effort (Azhar et al., 2008). Matta et al. (2018) further mention that BIM based sheets might be used as a VM tool for on-site operations. Nascimento et al. (2017) proposed a digital Obeya room (DOR) framework combining interdisciplinary project management, including 3D VM, and work-flow data to perform constructability analysis, and to determine and validate the work packages before production. This way, supply management is guided to minimize movement, the first-in-first-out principle is applied, and storage availability is verified. A combination of Lean/BIM not only controls production in the built environment but also predicts and prevents future problems. Moreover, Gemba Walks or the "going to Gemba" principle emphasizes personal observation for managers or directors to follow the works being done in the field, instead of relying on reports (Liker, 2004; Sacks et al., 2009a). In this sense, virtual walks on detailed BIM models are an easier and more convenient option for busy or remote managers.

Rapid model generation (V3)

Designers and cross-functional teams start projects by considering several alternatives in the set-based design methodology to find the best suit (Dave et al., 2013). BIM facilitates the rapid manipulation, layout, and generation of different design alternatives based on parametric relationships, and behavioral intelligence on object parameters and properties (Sanchez et al., 2016). Moreover, dependencies, pre-requisites, construction tasks, and resources can be identified and simulated in BIM (Sacks et al., 2009a, 2010; Eastman et al., 2011). The 4D visualization of construction schedules reduces the mental representations of co-builder schedules by simplifying the complex procedure and promoting the collaboration in design and construction (Bortolini et al., 2019). In such projects with multiple contractors, more detailed planning might unnecessarily reduce inventories, so software helps to visualize and educate the process (Alarcon et al., 2013b). Project alternatives can be generated and evaluated by different criteria such as structural, MEP, and sustainability performance to achieve maximum value for minimum costs with the help of automated quantity take-offs. Mahmood and Abrishami (2020) picked “automated generation of models and documents” as one of the most important components in building surveying. This evaluation not only helps the owner minimize wastes and generate flow but also helps the customer better define value on alternatives (Hijazi et al., 2009; Alarcon et al., 2013a; Al-Hattab and Hanzeh, 2015; Ciribini et al., 2016). The key point here is to delay decisions until the last responsible moment to avoid missing better alternatives because of rashness and lack of information (Ward et al. 1995; Dave et al., 2013).

Reuse of model for predictive analysis in BIM (V4)

Today, performing energy conversation and sustainability-related assessments (i.e. lightning, water, indoor environmental quality, waste management) becomes vital due to the climate change. Hence, BIM is considered as an effective tool for green buildings because of its level of detail in whole-building energy analysis with respect to different conservation measures, feasibility calculations of renewable energy technologies, and maintenance data diagnostics with coordination abilities (Lu et al., 2017). Furthermore, it is expected that while implementing the LC techniques in construction, BIM will be able to evaluate and automate changes in the construction tasks with dependencies within a short time interval. Thus, reusing the model for predictive analysis helps owners find the minimum cost within prerequisites and contractors maintain flow without excessive effort. At this point, LC and BIM positively interact to provide the best alternative.

Given this background, this study developed the above-mentioned 3 categories and 17 subcategories to explore the synergy between LC and BIM. In this context, the subcategories are explained in detail and relevant references are presented accordingly. Table 1 illustrates a summary of the categories and their underlying subcategories by providing an explanation regarding the link between LC and BIM.

Table 1. Categories and subcategories

Category	Code	Sub-Category	Explanation
Communication (C)	**C1**	Collaboration in design	Lean/BIM interaction harmonizes communication in the design process between individuals

	C2	Coordination and Collaboration among teams	Lean/BIM interaction facilitates teamwork and enhances collaboration among teams
	C3	Last Planner System Implementation (Safety, Fail-Safe in Lean-Real time access in BIM)	Lean/BIM interaction improves the LPS and improves safety measures by reduced workflow uncertainty
	C4	Object-based Communication	Lean/BIM interaction enables constant traceability and assessment by object-based communication
Production (P)	**P1**	Continuous Improvement	Lean/BIM interaction increases efficiency continuously by including all processes and people
	P2	Flexibility	Lean/BIM interaction improves the control of tolerances
	P3	Information Accuracy	Lean/BIM interaction improves information flow and accuracy
	P4	Improved planning and scheduling in BIM with JIT Delivery	Lean/BIM interaction ameliorates planning and scheduling
	P5	Production Control	Lean/BIM interaction enhances production control
	P6	Reducing Variability	Lean/BIM interaction reduces the variability in production to achieve project targets
	P7	Process Standardization	Lean/BIM interaction reduces the waste and inefficiency in activities and helps standardize construction processes
	P8	Systems Design for Flow and Value	Lean/BIM interaction helps build systems according to flow and value
	P9	Target value design	Lean/BIM interaction prioritizes the maximum customer value

Visualization (V)	**V1**	Designing out Errors	Lean/BIM interaction reduces design errors through visual abilities
	V2	Graphical information - Visual cues in Lean (Visual management)-Visualization in BIM for better representation of the design model	Lean/BIM interaction enhances the detailed representation of design models
	V3	Rapid model generation	Lean/BIM interaction enables rapid model generation
	V4	Reuse of model for predictive analysis in BIM	Lean/BIM interaction facilitates predictive analysis by reusing the design model

Research Methodology

A reproducible, systematic literature review is necessary to create new knowledge and insights by compiling the existing works (Mostafa et al., 2016; Tezel et al., 2020). In this study, the literature review covers the academic papers published between 2010-2020 and some other important studies from both the LC and BIM research domains. Therefore, studies separately exploring LC and BIM are used to generate a historical perspective to these terms.

After synthesizing the conceptual LC/BIM categories and subcategories from the literature review, for the analysis, the Analytical-Network-Process (ANP), a Multi-Criteria-Decision-Making (MCDM) method, was utilized to find the relationship and feedback among the factors, interdependent relationships among the decision alternatives, and attributes (Saaty, 1996).

MCDM methods are rather used to analyze more complex systems involving a fuller set of factors and requiring more sophisticated approaches. Some of these modeling techniques include but not limited to the analytical hierarchy process (AHP), ANP, data envelopment analysis (DEA), expert systems, goal programming, multi-attribute utility theory (MAUT), outranking, simulation, and scoring models (Sarkis and

Sundarraj, 2000). Each method has its own strengths and limitations but also rely on several common features such as conflict among criteria and incomparable units (Pohekar and Ramachandran, 2004, Mardani et al., 2015, Orji et al., 2020). On the other hand, “MCDMs are sometimes challenging for the construction industry due to the nature of the industry, complexity of projects, and fragmentation. Seth et al. (2018) listed certain challenges of MCDM application in the construction industry, which also apply to the decision-making criteria in this study. One major challenge was expressed as the competitive nature of the industry, which makes the evaluation of alternatives difficult in terms of deciding on the criteria and sub-criteria for selection. One other important challenge is that some factors are not possible to express in commensurable units, which rather reflect intangible aspects. This leads to complexity and fuzziness in factors in terms of both dealing with quantitative and qualitative criteria. Moreover, construction related decision models are difficult to structure in terms of various constraints affecting the problem. This might result in relative weights, priorities, risk analysis and generating scenarios. Finally, conflicting requirements from multiple stakeholders and multi-functional or multi-disciplinary networks make decision making processes even more complex, where internal and external constraints result in challenging MCDM treatment (Seth et al., 2018). Considering the temporary nature of construction projects, it can be asserted that MCDM treatment may result in complications in terms of making the best choice of MCDM.”

AHP developed by Saaty (2008) is one of the most used MCDM method in the literature (Mardani et al., 2015). The AHP technique provides the opportunity to decompose problems in a hierarchical structure, where top criteria is set at the top, criteria, sub criteria, and sublevels are presented at the bottom (Wang et al., 2009). However, AHP has static and unidirectional interactions of the criteria set with insufficient feedback across decision alternatives, criteria dimensions, and component factors (Triantaphyllou, 2000; Zhu et al., 2018). One other major limitation of AHP is that the criteria is considered as independent, where criteria in fact interact with each other (Orji et al., 2020). Scoring models, which is another MCDM method has been preferred as a method for decision making in terms of generating a strategically aligned portfolio showing the spending priorities of the business and resulting in sound decisions in high value projects (Cooper, 2003). In the outranking approach, the output of an analysis does not present a value for each alternative rather it shown an outranking relation on the set of alternatives (Belton and Stewart, 2002). Being an MCDM method, MAUT necessitates the identification of utility functions and weight for each attribute, which might be merged together in a synthesized criterion (Cinelli et al., 2014). DEA has capability to evaluate the performance of a set of homogeneous decision-making units with multiple input and outputs, and categorizes decision making units through linear programming into mutually exclusives and collectively exhaustive groups (Khezrimotlagh et al., 2019). Finally, expert systems might be used to handle MCDM problems using machine intelligence and expert knowledge avoiding human error and bias (Gu et al., 2019). Similarly, simulations are among the decision-based support systems used to find optimal solutions revealing robust options (Chandrasekaran and Goldman, 2007). In their study, Zhu et al. (2018) compared these decision making methods in terms of a set of criteria such as cost of implementing, data requirements, ease of sensitivity, and economic rigor. Depending on these criteria, they evaluated decision making methods as high, medium, and low. Based on this evaluation, they used AHP, which is a measurement technique that is based on the judgments of experts through pairwise comparisons to generate priority scales and to determine which element dominates the other element with respect to a given attribute (Saaty, 2008). Therefore, Zhu et al. (2018) implemented an expanded integration of AHP with the ANP.

Given this background, this study utilizes ANP to investigate the association between Lean and BIM. ANP is preferred to AHP for the fact that it provides the analysis of the research model in terms of the inner interdependencies on the hierarchical structure to reach the most comprehensive output (Saaty, 1996). ANP method is considered as an extension of the AHP method (Saaty, 1996) and it provides a better modeling of the interrelations among the decision levels/between clusters, and the elements within clusters (Zaim et al., 2014; Orji et al., 2020). In ANP, the variation occurs two way and looped relations are observed among the different levels (Sarkis, 2003). ANP also helps facilitating the inter-functional and inter-level discussions. It also allows to derive a decompositional method to address a wide variety of factors. One of the main advantages implied is that ANP calculations might be conducted on a managerial tool such as a spreadsheet (Sarkis and Surrandaj, 2002).

Both tangible and intangible criteria are allowed in the ANP to make the best decisions. The ANP approach is more detailed as it considers different relationships' connectivity by inter-functional and inter-level discussions, free from a strict hierarchy - i.e. used in the Analytical Hierarchy Process (AHP) (Garuti and Sadoval, 2005). In the

ANP, goals, criteria, sub-criteria, and alternatives are "calibrated" by clusters and determined by the relationships derived. The study conducted by Cil and Turkan (2013) generated an ANP-based model to determine the weights of an organization's Lean transformation determinants for the Lean enterprise transformation. Considering the interdependencies within and between elements and the multi-directionality of the elements, ANP is selected as the research method in this study.

The ratio scale priorities for the influence distribution of both the factors and clusters are evaluated in the study. First, the network criteria or sub-criteria are set to assess the base-interactions of the system. Then, the clusters and elements are evaluated based on the related networks; an inner dependency occurs when an element affects the other elements in the same component of the network and an outer dependency is observed when the influence of the elements is in different components. Eigenvectors assess the consistency, dominance, and priorities in the system. The composed matrices are additive to the super matrix that shows the dependencies. Lastly, the overall influence of all the elements is shown as the analysis output.

In this research, the conceptual model was composed based on an extensive literature review on Lean and BIM synergy. The review included relevant papers published in the construction and production focused journals such as (1) Production Planning and Control, (2) Journal of Construction Engineering and Management (JConstr.EM), (3) Engineering, Construction and Architectural Management (ECAM), (4) Journal of Management in Engineering (JME), and (5) Automation in Construction. The common keywords "Lean", "BIM", "synergy between Lean and BIM" , "ANP implementation in construction" were searched in the listed journals through search engines of Taylor and Francis, ASCE Library, Emerald, Science Direct, and Web of Science (WoS). The total number of relevant papers identified by the initial search was 223. However, not all the initial identified papers implied directly ANP implementation regarding Lean and BIM interaction. Thus, the initial collection was refined through a further visual examination. Only the studies clearlying identifying the details of Lean implementation along with BIM are regarded as valid. After the visual examination, 86 papers were finally considered. This refinement led to an initial list of 28 variables was composed. Next, the Delphi method was used to arrive at a decision with surveying a panel of experts. In contrast to other methods for problem solving, Delphi technique is a more reliable method in terms of solving problems with high uncertainty (Chan et al., 2001). Therefore, Delphi technique is a widely accepted method in construction engineering and management (CEM) research since the early 1990s (Hallowell and Gambatese, 2010). In this study, the first step as part of implementing Delphi technique started with the selecting expert panelists, who were chosen based on their experience in the construction industry, type of projects that they were involved, and having special knowledge in Lean construction and BIM using stratified sampling. Moreover, experts were chosen based on their experience in the real estate projects to specify valuable findings for the intended sector. The CEM research has not still yet agreed on a consensus in terms of the panel size but some researchers provide that the larger panel size leads to more reliable results (Murphy et al., 1998), where some other researchers reported no correlation between panel size and accuracy of the method (Boje and Murnighan, 1982). Major portion of the previous studies employed a panel size varying between 8 and 20 in their CEM studies (Hallowell and Calhoun, 2011; Chan et al. 2001). This study involved 18 experts in total to evaluate the questionnaire items. Three rounds were conducted to complete the Delphi study, which is in line with the observation of Dalkey et al. (1970) who reported that Delphi results are more appropriate after two rounds. A 5-point Likert scale was adopted to quantify the opinions of experts on items to reach a consensus. Kendall’s coefficient of concordance (W) was employed to test the level of consensus among the experts, which is highly employed way of testing level of consensus (Hon et al. 2012; Hallowell et al. 2011). A concordance coefficient of 1 corresponds to 100% consensus. In this study, the W value was calculated as 0.586. Since the study used Likert scale, inter-group comparison was tested with the Spearman’s rank correlation coefficient. The Spearman’s rank correlation coefficient exceeded the critical value at the level of significance, which was set as 0.05 proving that there is consistence between the different respondent groups (Ke et al. 2011). Finally, a correlation analysis was conducted regarding the variables in the Delphi study. Hence, Pearson correlation matrix was checked the correlation of different variables. The Pearson’s correlation coefficient for each item resulted in a high and positive correlation coefficient which is close to 1 indicating that the responses of the expert panelists on an item are similar across the three rounds of the Delphi study.

The content validity of the variables used to construct the ANP model was assessed through these rounds. The initial list was refined to 17 variables through the Delphi study. The identified variables are grouped under three categories as communication, production, and visualization. All the interviewees reported that they have at least 5 years of experience in both Lean and BIM practice and the average years of experience was determined as 12. The interviewees have an extensive experience in real estate projects mostly focusing on residential and commercial projects. Therefore, the questions were designed to collect data from such projects. The questions in the interviews are intended to gather information regarding the interrelated functions and how Lean practices promote BIM applications. Then, the pairwise comparisons and relative weights are determined (Chemweno et al., 2015; Deniz, 2017). Categorization of the identified variables led to a two-level hierarchy, where the top-level elements (clusters) are decomposed into lower-level attributes (nodes). The ANP can accommodate unequal number of sub-factors, whereas some techniques require equal grouping. This in turn might create complexity in subject treatment but composing a model comprising unequal number of sub-factors provides flexibility when establishing the model.

The Super Decisions software was used to execute the ANP calculations (Saaty, 2003). The relationships among the nodes are presented accordingly. After the input matrices, the software-generated big datasets of “Supermatrix”, “Limiting Supermatrix” and “Weighted Supermatrix” that are used to measure the importance weights of the nodes. This way, the determined clusters and nodes are compared and weighted. The interrelations among the model attributes are determined by a group of experts made up of both university professors and industry practitioners (three university professors who are experts in the LC and BIM concepts, and two practitioners who are currently implementing LC and BIM in the industry) using the Delphi method where three rounds of questionnaires are sent out to the group of experts, and the anonymous responses are aggregated and shared with the group after each round. At the end of rounds, incompatible responses were scrutinized, and a common attributes matrix was formed in order to maintain the reliability of the model. Also, an online questionnaire was designed and administered to construction professionals operating in the U.S. construction industry to evaluate the pairwise comparisons (see Appendix I). The respondents are selected based on their experience with Lean and BIM related projects. A total of 27 questionnaires were returned out of 65 sent resulting in a response rate of 41.5%. The respondents were selected among the members of the LCI, and the Lean construction practitioners were reached through the network of the International Group for Lean Construction (IGLC). The pairwise comparisons were evaluated by sixteen senior managers implementing both LC and BIM for more than 5 years, where most of the managers have been implementing LC and BIM for about 15 years. The steps followed in the study are summarized in Figure 2. Moreover, the performance of the model was tested with data from five different construction projects.

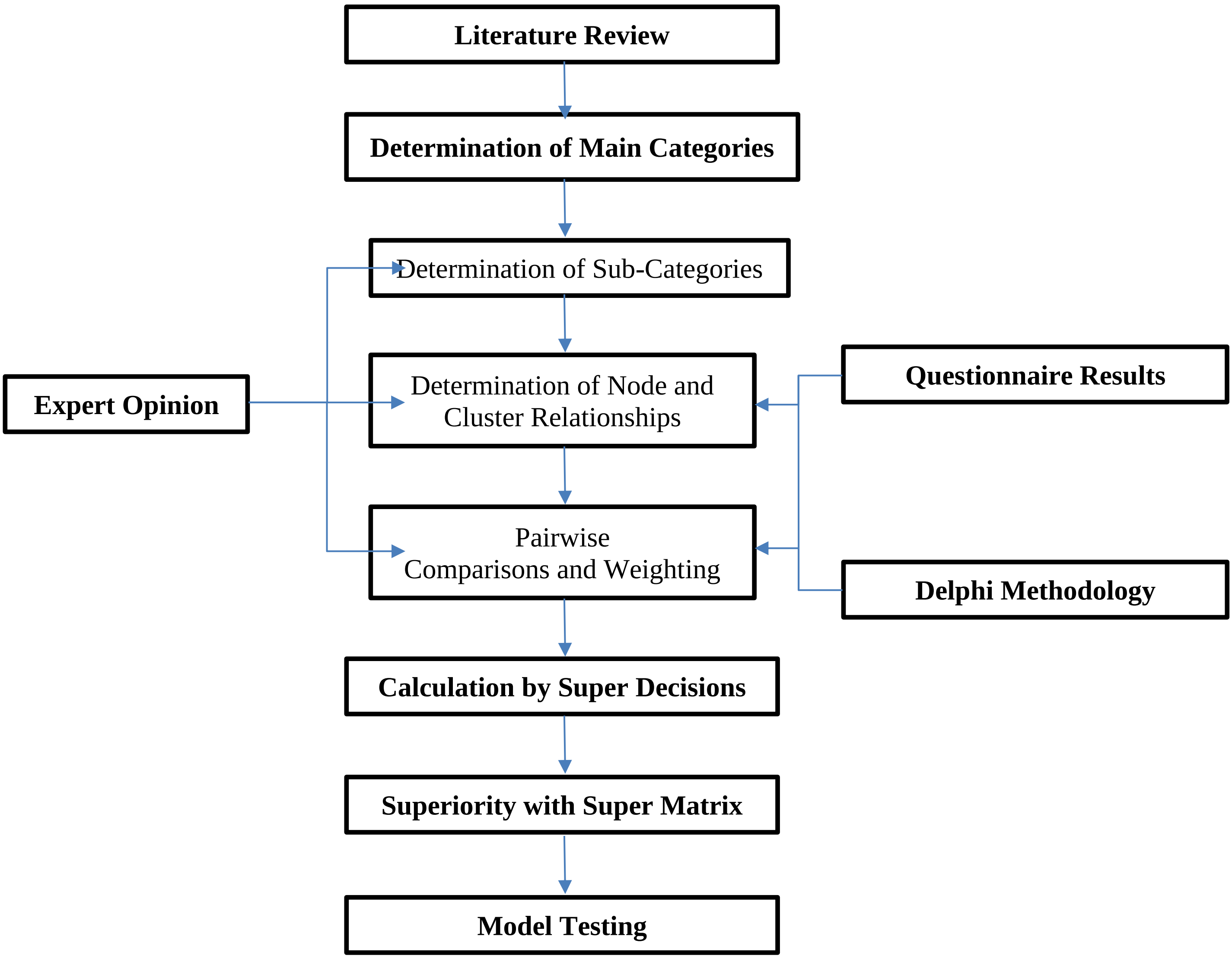

Figure 2. Research steps followed in the study

LC/BIM Interaction Model Construction

After an in-depth literature review of the Lean/BIM studies, a cognitive model was constructed which includes a total of 28 variables under three clusters. The review of the inputs by the professors and industry experts through the Delphi method either eliminated some unnecessary variables or merged the related ones, reducing the total variable number to 17, where the number of clusters remained at three, Communication, Production, Visualization. Several rounds of questionnaires were sent out to the expert group and their anonymous responses were gathered and shared with them at the end of each three rounds in the Delphi method. The analysis of the questionnaire data resulted in a common network that is also utilized as the input for the pairwise decision matrix. Moreover, with the help of the Delphi rounds, some of the variable names were changed to be able to better communicate the Lean/BIM concepts to the construction industry. For example, "Gemba Walks" was merged with the second Visualization (V2) variable. Moreover, the morning huddles discourse was removed from the Last Planner System Implementation (C3) variable before forming the ANP model as it is considered as a routine practice that is coordinated in weekly periods in the industry (based on the feedback provided by the expert team). To construct a comprehensive model, the professors and industry experts were mainly consulted with the concepts relating to the dynamic nature of LC and BIM. A final list of 17 variables under three categories formed the ANP model. The Lean/BIM interaction model hierarchy, overall goal, and the main and sub-criteria used with the relationship structure are presented in Figure 3. The factor groups (variables) are coded by the first letter of their corresponding group name.

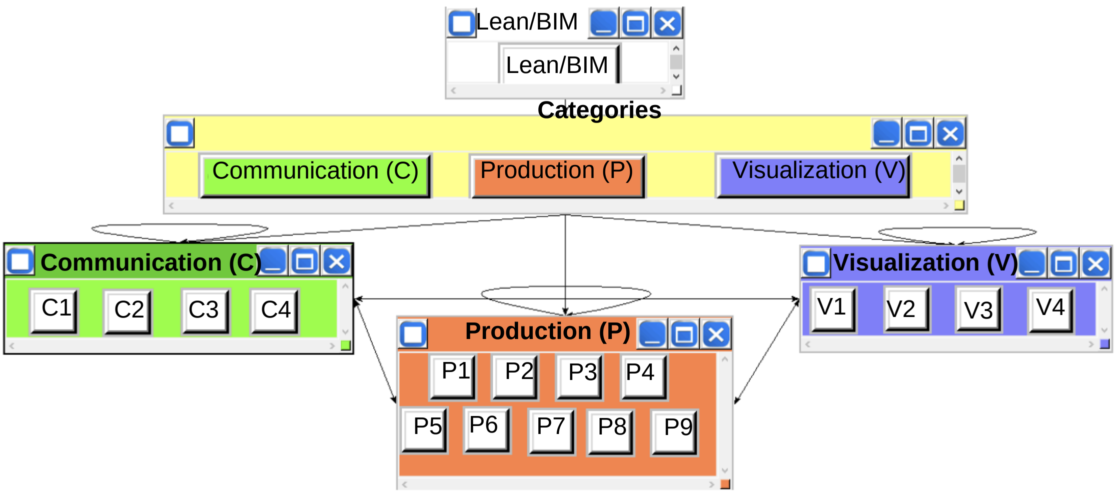

Figure 3. Lean/BIM interaction model

Pairwise Comparisons of the Interrelated Variables

The node connections of the structured model open the path for the pairwise comparison matrices. The comparison matrices and node connections are evaluated by the expert team's opinions from the Delphi to establish a common form. Later, according to the pairwise decision matrix, the group of experts evaluated the matrices for the importance weight of the attributes on a scale from 1 (equal) to 9 (extremely superior). The respondents avoided using the value "1" in the questionnaire as it does not indicate any superiority. A total of 34 matrices were evaluated for the clusters and nodes, all of them being smaller than the limiting values of inconsistency. Some of the matrices are presented in Tables 2-4.

Table 2. Interdependencies among the nodes for the Communication category

Communication (C) [Inconsistency: 0,0645]	C1	C2	C3	C4
Collaboration in design (C1)	1	1/4	1/2	2
Coordination and Collaboration among teams (C2)	4	1	1/2	4
Last Planner System Implementation (Safety, Fail-Safe in Lean-Real time access in BIM) (C3)	2	2	1	5
Object-based Communication (C4)	1/2	1/4	1/5	1

Table 3. Interdependencies among the nodes for the Production category

Production (P) [Inconsistency: 0,0720]	P1	P2	P3	P4	P5	P6	P7	P8	P9
Continuous Improvement (P1)	1	5	1/5	1/2	1/6	3	1/7	2	2
Flexibility (P2)	1/5	1	1/3	1/3	1/7	3	1/6	1/2	1/5
Information Accuracy (P3)	5	3	1	2	1/3	5	1/2	3	4
Improved planning and scheduling in BIM with JIT Delivery (P4)	2	3	1/2	1	1/4	5	1/4	4	2
Production Control (P5)	6	7	3	4	1	6	2	5	4
Reducing Variability (P6)	1/3	1/3	1/5	1/5	1/6	1	1/6	1/2	1/4
Process Standardization (P7)	7	6	2	3	1/2	6	1	5	5
Systems Design for Flow and Value (P8)	1/2	2	1/3	1/4	1/5	2	1/5	1	1/2
Target value design (P9)	1/2	5	1/4	1/2	1/4	4	1/5	2	1

Table 4. Interdependencies among the nodes for the Visualization category

Visualization (V) [Inconsistency: 0,0454]	V1	V2	V3	V4
Designing out Errors (V1)	1	2	5	2
Graphical information - Visual cues in Lean (Visual management)-Visualization in BIM for better representation of the design model (V2)	1/2	1	5	2

Rapid model generation (V3)	1/5	1/5	1	1/5
Reuse of model for predictive analysis in BIM (V4)	1/2	1/2	5	1

Importance Weights of the Attributes

The influence of each node was determined by the corresponding supermatrix. The supermatrix is established following those three steps;

1) The scores between the interacting elements of the pairwise comparison matrices lead to the generation of the unweighted supermatrix,
2) The weighted supermatrix is calculated by the multiplication of the unweighted supermatrix and cluster weights connected to the nodes,
3) A limiting supermatrix is formed by raising the weighted supermatrix to powers until all the columns corresponding to any node yield the same values (Erdem & Ozorhon, 2013).

The common weights are determined by the Delphi method after the collection of the responses from the questionnaire. To keep the model constant, the acceptable levels for inconsistency were set as 0.08 for a 4 × 4 matrix, and 0.10 for the bigger matrices (Saaty, 1994). The acceptable levels were satisfied for all the studied matrices which can be seen in the tables previous shown. Table 5 summarizes all the relationships within the nodes determined by the expert opinion from the Delphi and used in the model. For instance, according to the C1 column’s second row, Continuous Improvement (P1) is influenced by Collaboration in Design (C1). A similar approach was adopted for the remaining nodes. The importance of the clusters is presented in Table 6. According to Table 6, the Production cluster outweighs the other clusters and is determined as the prominent influencer for the Lean/BIM interaction in the construction industry, followed by the Communication and Visualization clusters.

Table 5. Relationships among the nodes

No	C1	C2	C3	C4	P1	P2	P3	P4
1	C1C2	C2C1	C3C2	C4C1	P1C4	P2C2	P3C1	P4C2
2	C1P1	C2C4	C3P1	C4C2	P1P2	P2P1	P3C2	P4C3
3	C1P3	C2P1	C3P3	C4P3	P1P3	P2P4	P3C3	P4P1
4	C1P4	C2P2	C3P4	C4P4	P1P4	P2P5	P3C4	P4P2

5	C1P6	C2P3	C3P6	C4P5	P1P5	P2P8	P3P1	P4P3
6	C1P8	C2P4	C3P7	C4P6	P1P6		P3P4	P4P5
7	C1P9	C2P6	C3V1	C4P8	P1P7		P3P5	P4P6
8	C1V1	C2P7	C3V2		P1P8		P3P6	P4P7
9	C1V2	C2V1			P1P9		P3P7	P4P8
10	C1V3	C2V2			P1V1		P3P8	P4P9
11	C1V4	C2V4			P1V2		P3P9	
12					P1V3		P3V1	
13					P1V4		P3V2	
14							P3V3	
15							P3V4	

Table 5. Relationships among the nodes (Cont'd)

No	P5	P6	P7	P8	P9	V1	V2	V3	V4
1	P5C2	P6C2	P7C2	P8C2	P9C1	V1C1	V2C1	V3C1	V4C1
2	P5C3	P6P1	P7C3	P8C3	P9C2	V1C3	V2P1	V3P1	V4P1
3	P5P1	P6P2	P7P1	P8P1	P9P1	V1P1	V2P3	V3P3	V4P3
4	P5P2	P6P3	P7P2			V1P3	V2V1	V3V4	
5	P5P3	P6P4	P7P3			V1P9	V2V3		
6	P5P4	P6P5	P7P4			V1V2	V2V4		
7	P5P6	P6P7	P7P5						
8	P5P7	P6P8	P7P6						
9	P5P8	P6V1	P7P8						
10	P5V1		P7V1						

Table 6. Importance weight of the clusters

No	Cluster	Importance Weight
1	Production	0,7574
2	Communication	0,1880
3	Visualization	0,0544

The importance weights of the nodes are ordered and summarized in Table 7. According to the table, the Production nodes such as Production Control (P5), Standardization (P7), Information Accuracy (P3), Continuous Improvement (P1), and Improved planning and scheduling in BIM with JIT Delivery (P4) are ranked as the first five parameters respectively, explaining an important portion of the model. Especially the first three nodes that are directly associated with defect-related issues are notable in this study. The Rapid model generation (V3) and Reuse of the model for predictive analysis in BIM (V4) nodes are the least important factors for the model.

Table 7. Importance weight of the nodes

No	Code	Node	Normalized by Cluster	Importance Weight
1	P5	Production Control	0,2148	0,1655
2	P7	Standardization	0,2138	0,1638
3	P3	Information Accuracy	0,1902	0,1457
4	P1	Continuous Improvement	0,1366	0,1044
5	P4	Improved planning and scheduling in BIM with JIT Delivery	0,1151	0,0871
6	C3	Last Planner System Implementation (Safety, Fail-Safe in Lean-Real time access in BIM)	0,3823	0,0727
7	C2	Coordination and Collaboration among teams	0,3772	0,0718
8	P8	Systems Design for Flow and Value	0,0416	0,0319
9	V1	Designing out Errors	0,6886	0,0301
10	C4	Object-based Communication	0,1382	0,0252
11	P9	Target value design	0,0311	0,0238
12	P2	Flexibility	0,0282	0,0216
13	P6	Reducing Variability – Online	0,0282	0,0216
14	C1	Collaboration in design	0,1022	0,0194
15	V2	Graphical information - Visual cues in Lean (Visual management)-Visualization in BIM for better representation of the design model	0,1964	0,0086

16	V4	Reuse of model for predictive analysis in BIM	0,0938	0,0041
17	V3	Rapid model generation	0,0211	0,0009

Discussion of Findings

The results indicate that better production control can be achieved with the integration of Lean and BIM. Previous studies also highlighted the reciprocal importance of production control for LC (Al-Hattab and Hanzeh, 2015; Ansah et al., 2016). Production control, which is promoted by the LPS implementation can be enriched by enabling the rational use of production resources with BIM. Since LPS provides an increased workflow reliability and work plan predictability, it is a very useful strategy for controlling the quality of assignments as well as increasing production system stabilization (Fernandez-Solis et al., 2013). As it is mentioned previously, rework related defects constitute 3.15%-4% of the contract value in residential construction projects, which is prone to be higher in more complex project types.

Previous studies focusing on the Lean/BIM integration reported substantially decreased rework in complicated projects such as airports (Koseoglu et al., 2018) and hospitals (Ghosh et al., 2014). In one of Sutter Health's hospital projects, the Lean/BIM implementation reduced rework by 15% (Dave et al., 2013). Automated codes, check sheets (Ansah et al., 2016), clash detection (Goyal and Gao, 2011), design charettes (Al-Hattab and Hanzeh, 2015), progress records, and augmented reality related new technologies enhance production control (Park et al., 2013), and promote the Lean/BIM interaction in the construction industry. In particular, clash detection saved 3-5% of the overall cost in a motors production plant (Eastman et al., 2011), $600,000 in an aquarium and over $1 billion in a hospital project (Wang et al., 2016, Mehrbod et al., 2019). Lean/BIM reduces the inefficiency induced by the traditional construction culture and helps achieve Standardization (P7) in the fragmented structure and diversified teams. The effect of the Lean/BIM synergy has the potential to establish a common experience for the teams with continuous and coordinated communication, leading to an improved flow. This is mainly achieved by the implementation of the LPS leading to successful collaborations in projects. LPS further provides more advantages for less rework and mistakes enhancing cooperation among team members. Standardizing planning and control processes will help LPS be implemented with more success leading to increased production planning and control (Lagos et al., 2017). This will cause standardization for a better value generation (Dong et al., 2013). Information Accuracy (P3) is improved with the Lean/BIM interaction because of the harmonized information and shared data flow across the project stakeholders. BIM does facilitate 3D models, clash detection, energy analysis, performance tracking (Alarcon et al., 2013a), and the LPS or VM related practices such as daily huddles or big rooms that minimize technical interoperability and information exchange related constraints (Tauriainen et al., 2016). The communication and visual abilities of BIM have the potential to facilitate kaizen and kaikau (Womack and Jones, 2003; Tezel et al., 2020). The integration of the continuous assessment ability of tasks in BIM with continuous improvement (P1) is also a crucial factor for the Lean/BIM integration in the industry. Spitler (2014) mentions that the core of Lean and BIM integration lies in the collaboration, which is fostered by the LPS. He further reports that it is the team's responsibility to work towards continuous improvement and achieve less waste. Hence, it is essential to motivate the team towards composing a constructible model is key in the integration. Improved planning and scheduling in BIM with JIT Delivery (P5) is provided through Lean/BIM interaction, where LPS provides a better visualization of the future and planning transparency with respect to data collected in Viana et al.'s (2010) study.

The Lean/BIM interaction also facilitates the LPS implementation (Safety, Fail-Safe in Lean-Real time access in BIM) (C3) and Coordination and Collaboration among teams (C2) that are found as the critical measures for the communication cluster. The LPS increases the resolution of production planning with minimum error tolerance (Goyal and Gao, 2011). If used together with BIM's ability to create 3D geometric models of different components, flow visualization (Li et al., 2018b) and better worker involvement (Ansah et al., 2016) are achieved. The use of BIM with the LPS can improve the PPC by 9% (Mahalingam et al., 2015) and enhance the work coordination. The LC principle of establishing long term partnership networks (Sacks et al., 2009a) plants seeds of trust to germinate a mutual understanding of goals. Moreover, a combined Lean/BIM process could improve transparency and offer innovative communication means for the project stakeholders such as BIM-based visual outputs of a construction sequence or clash points for the construction phase (Gerber et al., 2010) or BIM kiosks/stations (Bråthen and Moum, 2016) for the site personnel. Designing out errors (V1) is the prominent factor in the visualization cluster for the Lean/BIM utilization in the industry. Clash detection combines architectural, structural, MEP models and eliminates interactions among them that cause rework, financial, and time-related wastes. To eliminate such wastes, BIM enables the design team to visually control the clashes and to evaluate the construction process accordingly. Also, the coordinated production of different project drawings in the design phase and BIM objects' parametric behaviour help with Designing out errors (V1). Reuse of model for predictive analysis in BIM (V4) was found as one of the least important measures, which may be related to the current understanding of the industry that is not very sensitive enough to energy-related performance assessments. Nevertheless, this node may be more important in the future implementations of Lean/BIM due to the increasing awareness of and sensitivity to the issue in the construction industry. The model's cluster and node weights may indeed change with different countries and market conditions. For example, lack of financial resources is one of the most important barriers for LC implementations in many countries but UAE (Dubai) (Small et al., 2017). Similarly, the Lean/BIM implementation-related factors may change by different dynamics and conditions. Even if the factor weights change, the model and framework can still be used to assess the Lean/BIM synergy.

Dave et al. (2013) advised to introduce both LC and BIM gradually at the companies with a continuous improvement mindset. The authors' maturity model involving some forms of transparency, synchronized visualization, co-location of teams, early involvement, life cycle approach, target value design, BIM production management could be used to enhance the framework presented in the paper. As Andújar-Montoya et al. (2019) corroborate, only a small piece of Lean/BIM has been explored in the study. Hence, the framework proposed in this study might provide a basis for revealing and assessing the link between Lean/BIM in practice.

This study investigated the interaction between LC and BIM. The results revealed several important outcomes for those who are looking for the benefits and interactions brought by the utilization of both the LC and BIM concepts. The first and foremost finding of this research is that it puts production control at the core of the synergy between LC and BIM. The ANP model developed indicated that production is the most important cluster that might be promoted by the interaction of LC and BIM. This proves that companies desiring to improve their production processes shall invest more in LC and BIM tools and seek ways to benefit from this interaction as a priority. Especially, standardization, information accuracy, and continuous improvement were identified as the most important attributes of the production factor, which might lead industry practitioners to review and look for better practices in those attributes to improve their production processes. Besides, the ANP model emphasizes the importance of communication and visualization enhanced by the Lean/BIM integration. This finding suggests that it is essential for industry practitioners to improve their communication channels and focus on visualization opportunities to experience higher success in processes. At this point, the Lean/BIM integration might be a complete guide for them to revise their strategies in communication and enrich their visualization practices. Since the number of resources investigating Lean/BIM integration is limited in the literature, researchers might utilize the findings of this study to develop a more detailed model encompassing additional clusters and compare the findings accordingly. Furthermore, the model could be used to assess Lean/BIM implementations. Hence, the most important contribution of this study is to highlight the strong link between Lean/BIM, the priority areas in the Lean/BIM implementation, and the potential benefits from this link. The theoretical background for research and ANP model results reveal in this study the essential functions that are promoted by this strong synergy between Lean/BIM and their importance weights in practice. The ANP model presented in this study is constructed with the sixteen industry practitioners having a broad experience in the construction business. The industry practitioners are selected based on their level of experience in construction and experience with the complex projects. The experts are people who have collected experience in production management as well. Hence, the categories composed in the ANP model might be applied to a more generic business scenario, where production, communication, and visualization are key items to address problematic cases. The variables identified in this study such as coordination and collaboration, information accuracy, standardization, and production control are not only construction specific variables but also applicable to other industries manufacturing or healthcare industries. Considering real world problems require the careful consideration of dependence relations and feedback (Sipahi and Timor, 2010), the ANP model formed in this study provides insights regarding the dependence relations among a comprehensive list of variables of communication, visualization, and production in construction projects.

This study provides implications in terms of complementing the current literature by (i) defining variables related to production, communication, and visualization ; (ii) modeling the synergy between LC and BIM on a decisional ANP network encompassing three categories and 17 variables; (iii) revealing the dependence relations among the variables of production, communication, and visualization clusters; (iiii) presenting the importance weights of clusters and nodes reflecting their importance in the constructed model. The researchers can benefit from the findings of the model to develop more complex models including more variables to study LC and BIM interaction or construct similar models to further research the synergy with different set of variables. From a practical point of view, the model can help decision makers with accurate information to determine which LC and BIM parameters are most essential to achieve organizational objectives. The findings of the study can also lead practitioners to prioritize the LC and BIM elements to benefit from this interaction to achieve higher success in construction projects. The testing of the model in real projects can further provide insights for the practitioners by means of evaluating success in projects and consider the strength link between LC and BIM to revise and revisit their strategies.

Testing of the Model

The model was tested by a group of experts consisting of seven senior managers experienced in the LC and BIM implementation in the construction industry. The experts selected work in different states in the U.S. varying in terms of both demographics and size of construction projects executed. The managers provided real project data to test the model performance, which is a common approach adopted previously by several other researchers (Cheng & Li, 2005; Bu-Qammaz et al., 2009; Dikmen et al., 2010, Erdem & Ozorhon, 2013). The experts work at large-sized companies with significant experience in both domestic and international markets. The average turnover of the companies involved in the study is $900 million and the average company age is 29 years. The experts were asked to assign a rating for each parameter in the model and the level of success of the projects based on the project characteristics. The estimated values were calculated by multiplying the scores assigned for each parameter and importance weights derived from the model. The assessments were made on a Likert scale of 1-5.

The estimated project success values rated by the experts are compared with the importance weights generated by the ANP model. The results are summarized in Table 8. Table 8 indicates that the accuracy of the model is satisfactory. The percentage error (%error) was calculated by the formula shown in the table. The model seems to perform better in predicting more successful projects, where the success value is over 3.8, such as Cases 1 and 5 than less successful projects. The experts also provided feedback regarding the ANP model. They reported that the model might be further developed to include more clusters and functions deserve better emphasis in terms of implementing Lean with BIM. They further mentioned that they might benefit from the results of the Lean/BIM model to develop strategies for successful process execution and Lean/BIM implementation. Hence, it is predicted that companies can use this model as a roadmap for their LC and BIM implementation to successfully execute projects. Moreover, the ANP model might act as a comprehensive framework to reveal that production activities might be enhanced thanks to a successful integration of Lean and BIM.

Table 8. Applying the BIM/LEAN model to real projects.

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5
Success (Actual)	4.30	2.60	2.89	2.49	4.20
Success (Estimated)	3.90	2.42	3.10	2.22	4.12
$\%\text{error} = \left[\frac{\text{estimated} - \text{actual}}{\text{actual}}\right] \times \%100$	9.30	6.92	7.27	10.84	1.90

Conclusions

LC and BIM are increasingly used in the construction industry to improve the design, construction, and maintenance processes. Although, there is a rising number of studies concerned with utilizing these two concepts together, the combined use of LC and BIM is a relatively new phenomenon. Moreover, a framework for the joint utilization of these two concepts together has not been provided in most of those studies. This study developed an ANP model with a set of indicators derived for the three main model clusters for LC and BIM; Communication, Production, and Visualization with 17 different nodes that represent the factor groups. These factor groups were derived from the literature in the LC and BIM domain. The interrelations among the model parameters were determined by an expert team using the Delphi method. Later, the pairwise comparisons were performed by eight senior managers experienced in both LC and BIM. The responses were gathered with the Delphi method and then evaluated by the expert team to form a common understanding. The Super Decisions software was used to calculate the importance weight of each attribute. The model developed in the study shows that the Production cluster is prominent in the Lean/BIM implementation. Production Control (P5), Standardization (P7), Information Accuracy (P3), Continuous Improvement (P1), and Improved planning and scheduling in BIM with JIT Delivery (P4) are ranked as the first five most important parameters respectively. Visualization related parameters are mostly valued for the clash detection process. However, per the raising environmental concerns, the energy-related predictive performance analysis capability of BIM is expected to become a more important factor in the future. More generally, the more and less important nodes in the model could be reviewed in detail to evaluate the industry's understanding and perception of the Lean/BIM implementation.

According to the results of this study, production control and standardization are essential for the Lean/BIM in the construction industry to keep "the production line" under control, aiming to eliminate wastes and create maximum value, like in the manufacturing industry. The findings of the model are in line with the outcomes of previous studies from the construction and manufacturing domains. The validation of the proposed model on 5 real-life construction projects bridged the gap between theory and practice. Moreover, the projects selected for testing the model were conducted in different locations in the U.S. varying in terms of budget, size, and type. Hence, the results are generalizable in terms of evaluating the effectiveness of the Lean/BIM model and benefit from the findings for future projects. The study might further provide the key steering factors boosting the application of BIM in terms of improving LC. The results of the study can lead industry practitioners in terms of recognizing the important steering factors to actualize BIM tools along with the essential objectives of LC. The ANP model might act as a guide for the BIM managers and LC professionals in terms of prioritizing the steering factors and develop early actions towards eliminating waste and generating value.

The limitations of the study are the difficulty in data collection because of the limited number of qualified professionals, and market and country-related factors affecting an individual's subjective assessment of the comparison matrices. Moreover, the study did not explicitly consider the newer technologies such as IoT, augmented reality, and artificial intelligence. Instead, the BIM variables were rather investigated in terms of their functioning ability. The newer technologies were implicitly embedded into variables such as better visual representation of the model or object-based communication. Therefore, this might be listed as a limitation of the study recommending that newer models including those items shall be developed to thoroughly discuss the impact of innovative approaches.

For future work, the performance of the framework can be tested with additional experts and on different projects. The framework may be used for construction companies to assess their Lean/BIM integration for increased project success. Also, the model categories and subcategories can be reviewed for suitability. It is hoped that both researchers and practitioners will benefit from the findings of this study and use the model and discussions for LC and BIM implementations.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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<APPENDIX>

A CONCEPTUAL FRAMEWORK FOR LEAN CONSTRUCTION PRACTICES AND BUILDING INFORMATION MANAGEMENT IN THE CONSTRUCTION INDUSTRY QUESTIONNAIRE

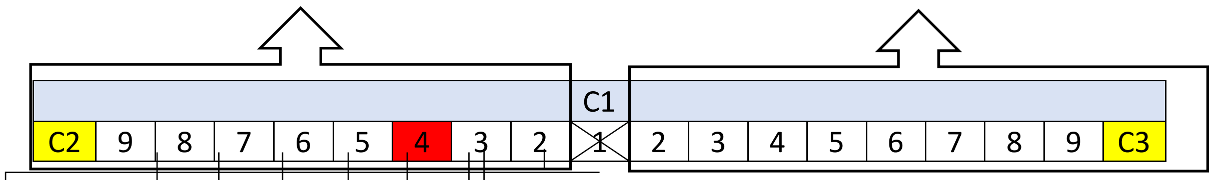
-By SuperDecisions-

Pairwise Comparisons

Please examine the interdependencies among nodes with respect to the given range.

i.e. If you compare C1 cluster, in between C2 and C3;

C2 is superior to C3 / C3 is superior to C2



Verbally;

9. C2 is Extremely More Important than C3
8. C2 is Very Strongly to Extremely More Important than C3
7. C2 is Very Strongly More Important than C3
6. C2 is Strongly to Very Strongly More Important than C3
5. C2 is Strongly More Important than C3
4. C2 is Moderately to Strongly More Important than C3
3. C2 is Moderately More Important than C3
2. C2 is Equally to Moderately More Important than C3

Please do not select the value of 1, as these matrixes are to evaluate the superiority over each node.

You can fill the box with Red color to show your choice.

Thank you for your effort !

Table 1. Categories and Subcategories for Lean/BIM Applications.

Category	Code	Sub-Category	Explanation
Communication (C)	**C1**	Collaboration in design	C1 facilitates Lean&BIM
	C2	Coordination and Collaboration among teams	C2 facilitates Lean&BIM
	C3	Last Planner System Implementation (Safety, Fail-Safe in Lean-Real time access in BIM)	C3 facilitates Lean&BIM
	C4	Object-based Communication	C4 facilitates Lean&BIM
Production (P)	**P1**	Continuous Improvement	P1 facilitates Lean&BIM
	P2	Flexibility	P2 facilitates Lean&BIM
	P3	Information Accuracy	P3 facilitates Lean&BIM
	P4	Improved planning and scheduling in BIM with JIT Delivery	P4 facilitates Lean&BIM
	P5	Production Control	P5 facilitates Lean&BIM
	P6	Reducing Variability – Online	P6 facilitates Lean&BIM
	P7	Standardization	P7 facilitates Lean&BIM
	P8	Systems Design for Flow and Value	P8 facilitates Lean&BIM
	P9	Target value design	P9 facilitates Lean&BIM
Visualization (V)	**V1**	Designing out Errors	V1 facilitates Lean&BIM
	V2	Graphical information - Visual cues in Lean (Visual management)-Visualization in BIM for better representation of the design model	V2 facilitates Lean&BIM
	V3	Rapid model generation	V3 facilitates Lean&BIM
	V4	Reuse of model for predictive analysis in BIM	V4 facilitates Lean&BIM

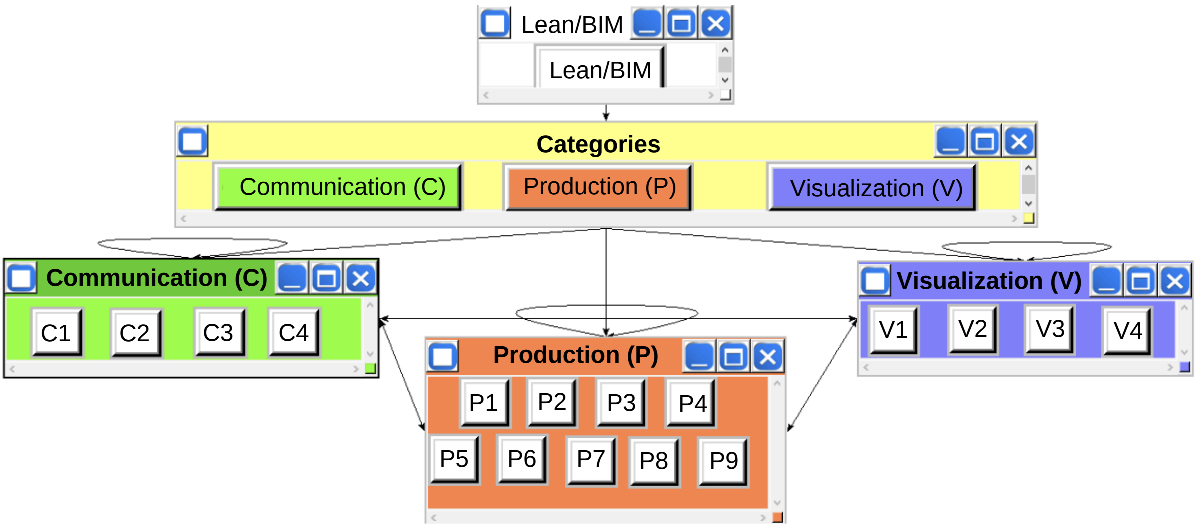


Figure 1. Comparison Structure

COMPARISONS TO FILL

1. *Clusters*

Categories																		
C	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	P
C	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	V
P	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	V

2. *Nodes*

Communication (C)																		
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	C2
C1	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	C3
C1	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C2	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	C3
C2	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C3	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4

Production (P)																		
P1	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	P2
P1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	P3
P1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	P4
P1	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	P5
P1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	P6
P1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	P7
P1	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	P8
P1	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	P9
P2	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	P3
P2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	P4
P2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	P5
P2	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	P6
P2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	P7
P2	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	P8
P2	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	P9
P3	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	P4
P3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	P5

P3	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	P6
P3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	P7
P3	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	P8
P3	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	P9
P4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	**7**	8	9	P5
P4	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	P6
P4	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	P7
P4	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	P8
P4	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	P9
P5	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	P6
P5	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	P7
P5	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	P8
P5	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	P9
P6	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	P7
P6	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	P8
P6	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	P9
P7	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	P8
P7	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	P9
P8	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	P9

Visualization (V)																		
V1	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	V2
V1	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	V3
V1	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	V4
V2	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	V3
V2	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	V4
V3	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	V4