Ahuja, R, Sawhney, A and Arif, M

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Article

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Developing Organizational Capabilities to Deliver Lean and Green Project Outcomes using BIM

Abstract (max. 250 words)

Purpose: This paper describes the process through which an organization develops organizational capabilities by tapping the technical skills and social skills of its employees in the use of BIM to deliver lean and green project outcomes. The resulting framework for BIM-based organizational capabilities development comprising of three hierarchical layers—technology, process and outcomes—is explained.

Design/methodology/approach: For this study**,** BIM has been identified as an enabler and a process for achieving lean and green outcomes on construction projects. Based on a detailed literature review, this paper identifies the organizational capabilities needed by the Architecture, Engineering and Construction (AEC) organizations to effectively implement BIM on construction projects. The study has been conducted through a sequential mixed-method approach involving semi-structured interviews, focus groups, and qualitative comparative analyses.

Findings: It was discovered that to attain desired project outcomes, an organization needs to embrace an underlying BIM adoption culture not only within its project teams but also within the organization as a whole. The study also concluded that an integrated approach for BIM usage—connecting it with lean and green initiatives—on construction projects resulted in improved project outcomes, especially ones targeting lean and green aspects of improvements.

Practical implications: The proposed outline for BIM-based organizational capabilities will help the organizations focus on the 'human factors' along with the technical factors while striving for successful usage within their organizations.

Originality/Value: Using the organizational capabilities matrix, this paper highlights the importance of technical and social skill sets of an individual employee and their role in developing the organizational capabilities to gain the desired lean and green outcomes.

Keywords: Building Information Modelling (BIM); AEC sector; BIM capabilities, lean principles, green principles, organizational capabilities

Article Classification: **Research Paper**

Introduction to BIM, Lean and Green Paradigms

The built environment sector is an integral part of the global economy and plays an important role in urbanization and improved quality of living. Sustained growth, especially in emerging economies, is causing demand side pressures on the sector. In a globalized economy, the sector also faces supply side pressures to adopt green principles and reduce all types of waste. Architectural Engineering and Construction (AEC) organizations are striving to attain lean and green results by improving the efficiency and management of construction projects. It is becoming increasingly important for AEC organizations to save time, resources, energy and cost on the projects that they deliver (Kumaraswamy and Dulaimi, 2001). Today, most construction work is carried out in the form of complex projects and hence, good project management is considered crucial in achieving the desired project outcomes (Maylor et al., 2008). Construction projects need to be expertly managed not only in terms of schedules and budgets, but also in terms of quality and environmental impacts (Formoso et al., 2002). Given the current conditions and overall status of the global AEC sector, the sector must start thinking about measures for bringing in the required change and continuous improvement (Sawhney et al., 2014).

While most of the recent construction-related studies have focused on the reduction of waste, increase in productivity, improvement in process efficiency, or minimization of environmental impacts, limited research has been done to develop a holistic organizational level framework that combines all these improvements. As a result, AEC organizations take a fragmented view of the environment related improvements (green initiatives) and the process related (lean principles based initiatives) improvements (Cone, 2013). Driven by a plethora of external and internal influences, the construction industry has independently embraced lean principles and green initiatives. Prima facie synergies have been reported between these two paradigms. It is envisioned that when tapped and adopted in unison, these paradigms may yield additional benefits for the construction projects (Cone, 2013). Since intuitively there are overlaps between these two improvements areas, AEC organizations must look at mechanisms that allow them to undertake both improvements simultaneously. This research investigates Building Information Modelling (BIM) as such a mechanism to amalgamate improvements that stem from adopting green practices and lean principles independently. In the following sub-sections, these three areas are described in more detail with the aim of introducing the idea of looking towards an organizational strategy for AEC organizations that promotes lean and green project outcomes by using BIM. The three paradigms: BIM, lean and green are complementary (Koskela et al., 2010) and often used independently to address quality, waste, and environmental impacts in construction. In this research, a framework is developed in which BIM is used as a lever to collectively achieve lean and green project outcomes.

Literature Review—BIM and its linkage with Lean and green

As the construction industry faces a paradigm shift to increase productivity, efficiency, reduced lead times, reduced lifecycle costs, enhanced quality and sustainability, BIM is being seen as a mechanism to gain these benefits. Past research (Arayici et al., 2012; Eastman et al., 2011) suggests that implementation of BIM on projects is a way to overcome various challenges faced by the construction industry today. The potential of BIM to reduce designers' efforts on production-oriented tasks and automate repetitive tasks, makes it more valuable development in recent years (Singh et al., 2017).

BIM promotes environmentally friendly design (Krygiel and Nies, 2008; Schlueter and Thesseling, 2009) thereby allowing the industry to advance the green paradigm. Past research has shown that BIM can be incorporated with the LEED rating system to streamline the certification process and save substantial time and resources which would otherwise be required using traditional methods (Azhar et al., 2011; Azhar and Brown, 2009; Barnes and Castro-Lacouture, 2009). BIM is found imperative for delivering sustainable projects with its capability to perform energy analysis, provide design to optimize energy consumption and process visualization (Rahman et al., 2013). Improved design and building performance are the two most significant benefits of BIM when used for sustainable building design.

BIM facilitates lean measures through design to construction to occupancy (Gerber et al., 2010) and at the same time contributes directly to lean goals of waste reduction, improved flow, reduction in overall time, improved quality by utilizing clash detection, visualization and collaborative planning (Dave et al., 2013; Oskouie et al., 2012). Improved project performance with reduced coordination issues has been reported as one of the major lean benefit of implementing BIM on construction projects (Johansson et al., 2014; Mahalingam et al., 2015). After identifying the interaction between BIM and lean, it was further suggested that the BIM maturity levels can be enhanced by implementing lean on projects (Hamdi and Leite, 2012). The potential application of BIM in the construction industry helps to eliminate construction waste during the design and pre-construction phase (Ahankoob et al., 2012). A BIM-enabled pull flow construction management software system, KanBIM, based on the last planner system showed that the system holds the potential to improve work flow and reduce waste (Sacks, Koskela, et al., 2010; Sacks, Radosavljevic, et al., 2010). Considering the connections between BIM, lean and green, development of BIM implementation strategies have also been suggested (Forgues et al., 2014).

Although a robust body of literature exists with detailed information on these three paradigms individually, there is still a gap in research and practice with respect to combining BIM, lean and green into one framework at the organisational level. This paper explores and synthesises the three complementary paradigms of BIM, lean, green into a framework for helping design and construction organizations overcome challenges and attain greater benefits.

Research Context—Organizational Capabilities

This research was aimed at developing an understanding of how design and construction organizations develop capabilities that help them utilize BIM to deliver lean and green project outcomes. By combining the findings from literature review, expert interviews, focus groups, and case studies a framework was developed that helps understand the journey an organization undertakes in developing these BIM capabilities. This framework was then tested and validated using case study data by applying crisp-set qualitative comparative analysis (csQCA), a research method developed by Charles Ragin in the 1980s (Ragin, 2013). The following key steps were followed in this research and are described in the next sections of this paper:

1. Establishing the definition and importance of capabilities of an organization
2. Identifying BIM functions and capabilities
3. Identifying lean and green project outcomes
4. Developing a BIM based organizational capabilities framework
5. Testing and validating the framework

Organizational Capabilities: Definition and Importance

McKinsey and Company (2010) defines the term ‘organizational capability’ as ‘anything an organization does well that drives meaningful business results’. Capability is also connected to the identity and personality of an organization that in turn is defined by the collective skills, abilities and expertise of the organization (Ulrich and Smallwood, 2004). Capability has also been defined as an ‘invisible asset’ that help transform inputs into outputs of greater worth (Amit and Schoemaker, 1993). While some use the terms competence and capability interchangeably, in the literature competence is linked to the technical aspects and capability is connected to the social and leadership aspects (Ulrich and Smallwood, 2004). These have also been defined along the individual, project and organizational dimensions, especially in project-based organizations (Davies and Brady, 2016; Loufrani-Fedida and Missonier, 2015).

Capabilities are the outcome of the investments in staffing, training, compensation, communication and other human resource areas of an organization (Ulrich and Smallwood, 2004). Discussing the ‘operational capability’, Winter (2003) states that the operational capabilities help the organizations to improve and sustain their performance. The organizational capabilities are key intangible assets and emerge when a company delivers on the combined competencies and abilities of its individuals (Ulrich and Smallwood, 2004). Further, Selçuk Çıdık et al. (2017) uses the concept of ‘innovative capability’ by describing it as the capability of a proposed solution to enable practitioners to establish novel ways of doing things for improvement.

Any technology adoption and implementation approach concerns the users involved, as much as the technology itself. For a successful technology adoption within an organization, it is necessary to engage the actual users in the adoption. It is necessary to ensure that their skills and understanding increases, thus allowing the entire organization to build up its capabilities. Various studies have also emphasized that organizations should focus on developing their capabilities, thus creating value and sustainability in the competitive environment (Chen and Fong, 2013; Too, 2012). In order to overcome the competitive challenges involved in the adoption, it is imperative for top management to devote more attention towards the improvement of critical business processes and develop and deploy a range of capabilities around the core processes (Cemal et al., 2006; Collis, 1994).

Operational innovation has been described as one of the major ways to stimulate growth in organizations which requires major changes in how their departments conduct the work and relate to one another. The necessary innovations are not limited to individual departments but involve end-to-end processes that cross departmental boundaries. The operational innovation efforts begin in an organization at its grassroots by people who are passionate and committed to operational change in the organizations, and from this group, a leader spearheads the innovation effort and helps the organizations to set its performance goals (Collis, 1994). Operational innovation is a step change which moves the organization to an entirely new level and it is seen that the organizations that inculcate operational innovation in their culture are most often the ones who are successful in achieving their desired outcomes (Hammer, 2004). With this understanding of an organization’s capabilities, this paper identifies different BIM capabilities which can be developed by the AEC organizations by using various BIM functions.

Identification of BIM functions and BIM capabilities

Thirty-three native BIM functions, as listed in Table 1, were identified through an extensive literature review and were traced back to the BIM Handbook (Eastman et al., 2011). Semi-structured interviews and focus groups were conducted with seven industry experts along with an in-depth literature review to then converge on fifteen BIM capabilities. The actual titles of the BIM capabilities were derived from an extensive literature review that has been listed in Table 2. Experts validated these BIM capabilities and helped create linkages between the thirty-three native BIM functions. These linkages are captured in Figure 1.

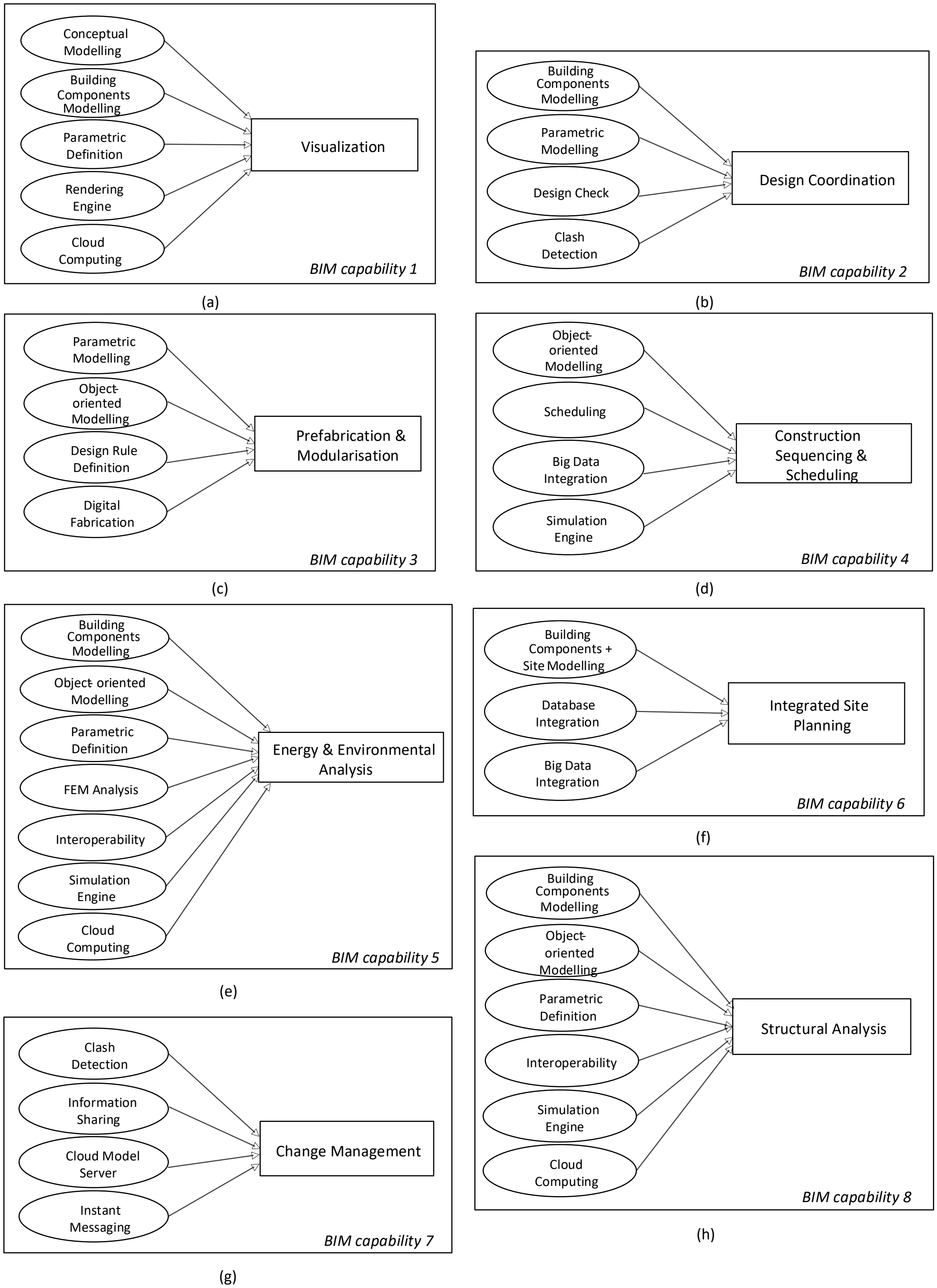
Table 1: Native BIM Functions

S.No.	Native BIM functions	S.No.	Native BIM functions
1.	Conceptual Modelling	18.	Object-oriented Modelling
2.	Building Components Modelling	19.	Constructability Analysis
3.	Parametric Definition	20.	Scheduling
4.	Rendering Engine	21.	4D Simulation
5.	Cloud Computing	22.	Interoperability
6.	Parametric Modelling	23.	FEM Analysis
7.	Design Check	24.	Simulation Engine
8.	Clash Detection	25.	System Check
9.	Information Sharing	26.	Specification Definition Integration
10.	Cloud Model Server	27.	Spreadsheet Application
11.	Instant Messaging	28.	Design Rule Definition
12.	Model Management	29.	Digital Fabrication
13.	Site Modelling	30.	Laser Scanning
14.	Database Integration	31.	Automated Components Recognition
15.	Big Data Integration	32.	FM Database
16.	RFID Data Integration	33.	FM Application
17.	Decision Making	*From* (Eastman et al., 2011)	

Table 2: BIM capabilities

S.No.	BIM capabilities	References
1	Visualization	(Azhar et al., 2008; Cory, 2015; Ding et al., 2014; Johansson et al., 2015; Wang, Wang, et al., 2014)
2	Design coordination	(Ciribini et al., 2016; Gijezen et al., 2009; Hooper and Ekholm, 2010; Lee et al., 2015; Liu et al., 2017; Wang and Leite, 2016)
3	Prefabrication and Modularization	(Abanda et al., 2017; BorjeGhaleh and Sardroud, 2016; Eastman et al., 2011; Ramaji and Memari, 2015; Seeam et al., 2013; Singh et al., 2017)
4	Construction sequencing and Scheduling	(Boton et al., 2015; Faghihi et al., 2014; Hartmann et al., 2012; Kim et al., 2016; Konig et al., 2012; Wang, Weng, et al., 2014; Zhang et al., 2013)

5	Energy and Environmental Analysis	(Abanda and Byers, 2016; Ajayi et al., 2015; Alwan et al., 2015; Gourlis and Kovacic, 2017; Schlueter and Thesseling, 2009; Shadram et al., 2016; Shrivastava and Chini, 2012; Wong and Zhou, 2015)
6	Integrated Site Planning	(Karan and Irizarry, 2015; Kumar and Cheng, 2015; Ma et al., 2005; Wang et al., 2016)
7	Change Management	(Langroodi and Staub-French, 2012; Liu et al., 2014; Pittet et al., 2014; Sawhney et al., 2017; Zada et al., 2014)
8	Structural Analysis	(Alirezaei et al., 2016; Cabaleiro et al., 2014; Chi et al., 2015; Lee et al., 2012; Yalcinkaya and Singh, 2015)
9	MEP System Modelling	(Bosché et al., 2014; Chen et al., 2012; Hu et al., 2016; Khanzode et al., 2008; Pilehchian et al., 2015; Wang et al., 2016; Yung et al., 2014)
10	Quantity Take-off	(Choi et al., 2015; Lee et al., 2014; Liu et al., 2016; Lu et al., 2016; Monteiro and Poças Martins, 2013)
11	Facility Management	(Kang and Hong, 2015; Kassem et al., 2015; Liu and Issa, 2013; Shi et al., 2016; Wetzel and Thabet, 2015)
12	Constructability Analysis	(Jiang et al., 2014; Kannan and Santhi, 2013; Kifokeris and Xenidis, 2017; Shrivastava et al., 2017; Tauriainen et al., 2015; Yeoh and Chua, 2014)
13	Collaboration & Coordination	(Beach et al., 2017; Becerik-Gerber and Rice, 2010; Liu et al., 2017; Ma and Ma, 2017; Mignone et al., 2016; Wang and Leite, 2016)
14	BIM for As-Built	(Bosché et al., 2014; Dore and Murphy, 2014; Golparvar-Fard et al., 2011; Jung et al., 2014; Park and Cai, 2017; Pătrăucean et al., 2015; Woo et al., 2010; Zeibak-Shini et al., 2016)
15	BIM for Supply Chain Management	(Aram et al., 2013; Babič et al., 2010; Grilo and Jardim-Goncalves, 2011; Irizarry et al., 2013; Jun-Qing and Hui-Min, 2011; Khalfan et al., 2015; Papadonikolaki and Wamelink, 2017)



Conceptual Modelling
Building Components Modelling
Parametric Definition
Rendering Engine
Cloud Computing
Visualization
BIM capability 1
(a)
Building Components Modelling
Parametric Modelling
Design Check
Clash Detection
Design Coordination
BIM capability 2
(b)
Parametric Modelling
Object-oriented Modelling
Design Rule Definition
Digital Fabrication
Prefabrication & Modularisation
BIM capability 3
(c)
Object-oriented Modelling
Scheduling
Big Data Integration
Simulation Engine
Construction Sequencing & Scheduling
BIM capability 4
(d)
Building Components Modelling
Object oriented Modelling
Parametric Definition
FEM Analysis
Interoperability
Simulation Engine
Cloud Computing
Energy & Environmental Analysis
BIM capability 5
(e)
Building Components + Site Modelling
Database Integration
Big Data Integration
Integrated Site Planning
BIM capability 6
(f)
Clash Detection
Information Sharing
Cloud Model Server
Instant Messaging
Change Management
BIM capability 7
(g)
Building Components Modelling
Object-oriented Modelling
Parametric Definition
Interoperability
Simulation Engine
Cloud Computing
Structural Analysis
BIM capability 8
(h)

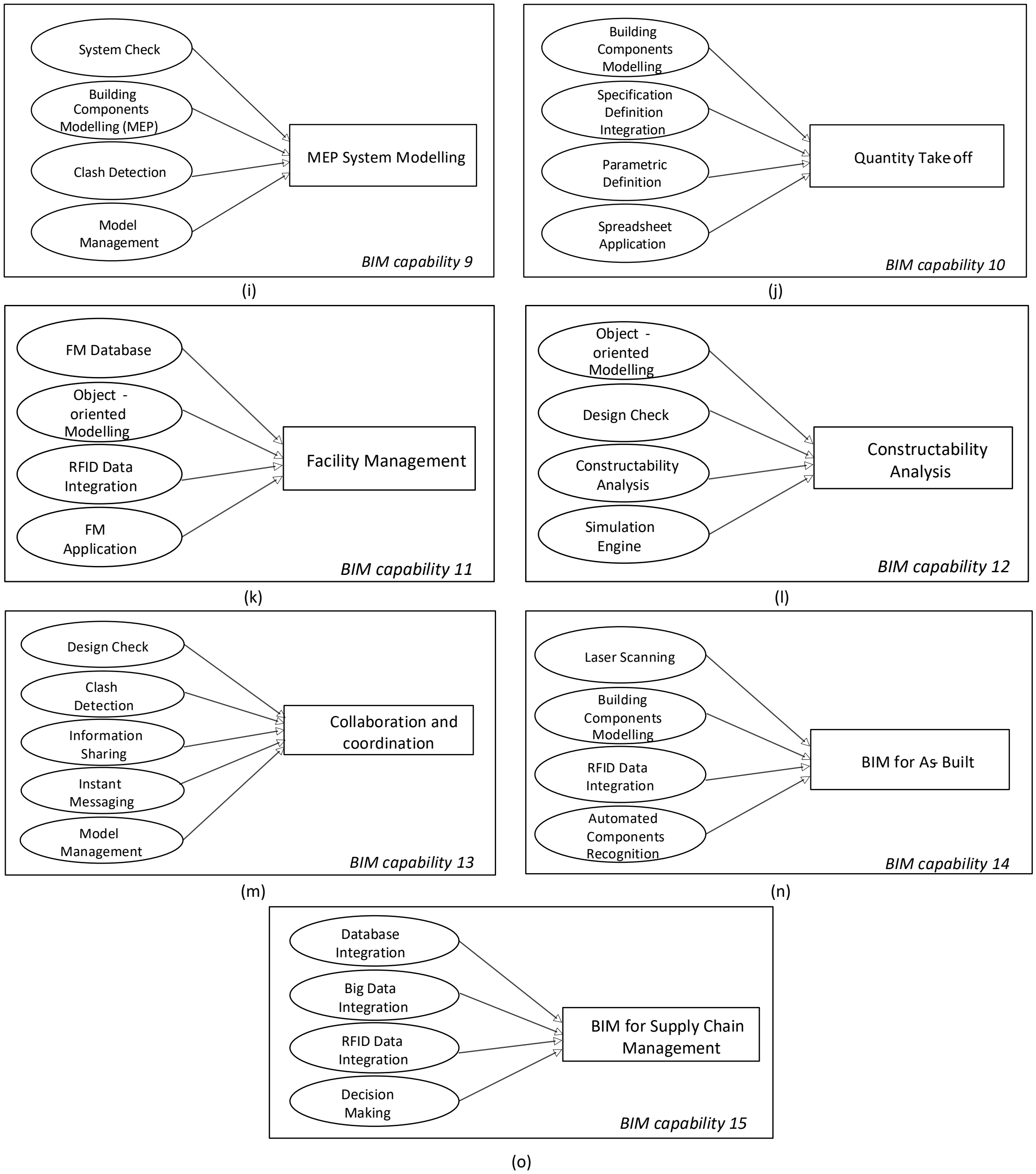


Figure 1: Native BIM functions leading to BIM capabilities

Identification of Lean and Green Project Outcomes

Understanding the need to sustain in the competitive markets, AEC organizations strive to attain efficient solutions and outcomes. While focusing on reducing waste and inefficiencies that exist in the design and construction processes the industry is embracing lean and green principles. Various researchers (Ahuja et al., 2017; Alarcón et al., 2005; Bae and Kim, 2008; Hill and Bowen, 1997; Koranda et al., 2012; Ogunbiyi et al., 2014; Peng and Pheng, 2011) from around the globe have documented various lean and green benefits that projects can attain. Using this extensive literature a cross-analysis was conducted to document a list of green outcomes attained when lean principles were adopted and a list of lean outcomes attained when green principles were adopted on projects. The lean benefits obtained by adopting green principles is shown in Figure 2 and the green benefits attained by implementing lean principles is shown in Figure 3.

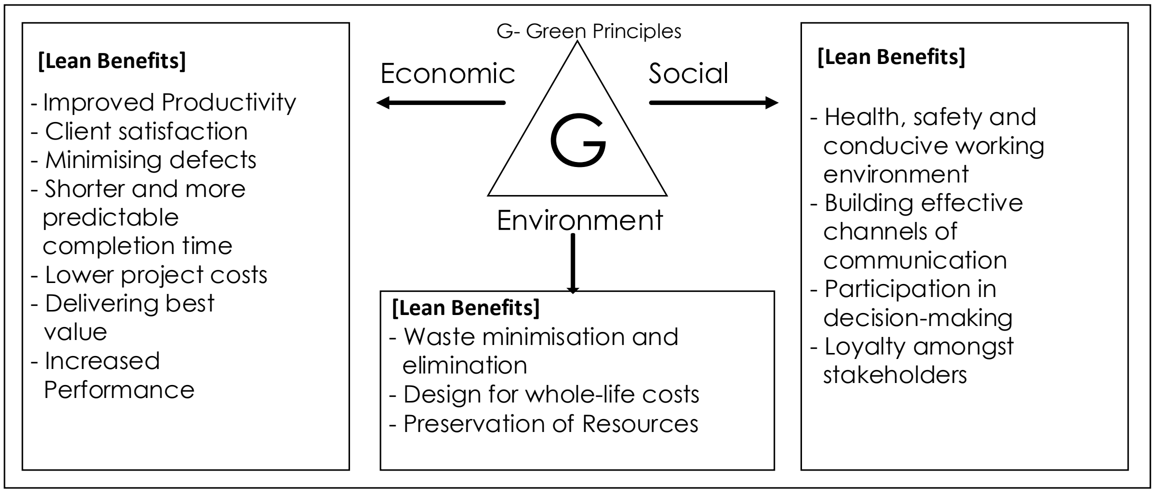


Figure 2: Lean benefits of applying green principles to construction projects

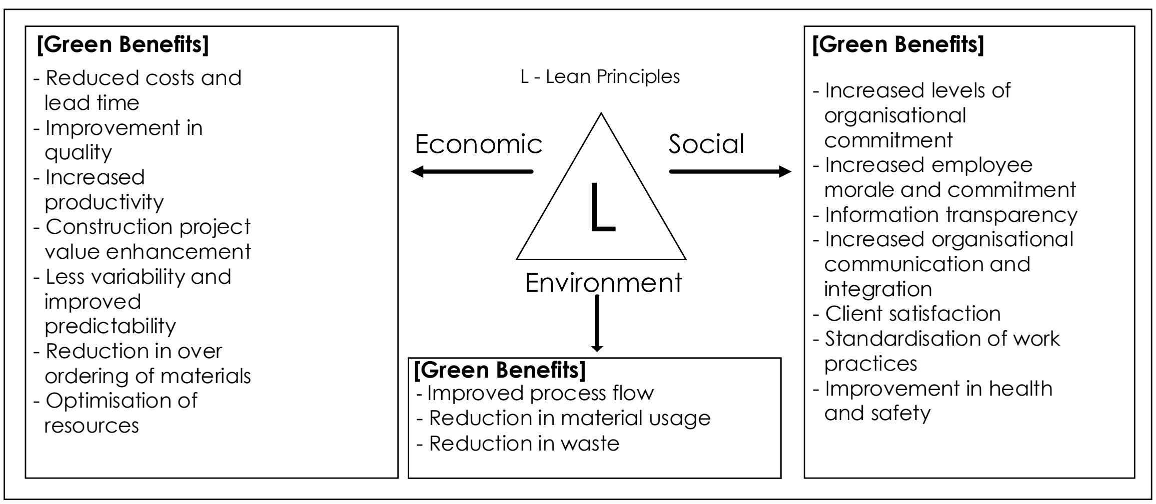


Figure 3: Green benefits of lean implementation on construction projects

The listed (Figure 2 and Figure 3) economic, social, and environmental benefits were then discussed with the industry experts and focus group was conducted to understand the synergies between the two paradigms. Eventually ten lean and green project-level outcomes as shown in Figure 4 were identified for developing the proposed organizational capabilities framework. These are the overlapping outcomes an organization can expect to achieve when lean principles and green practices are implemented together on a project.

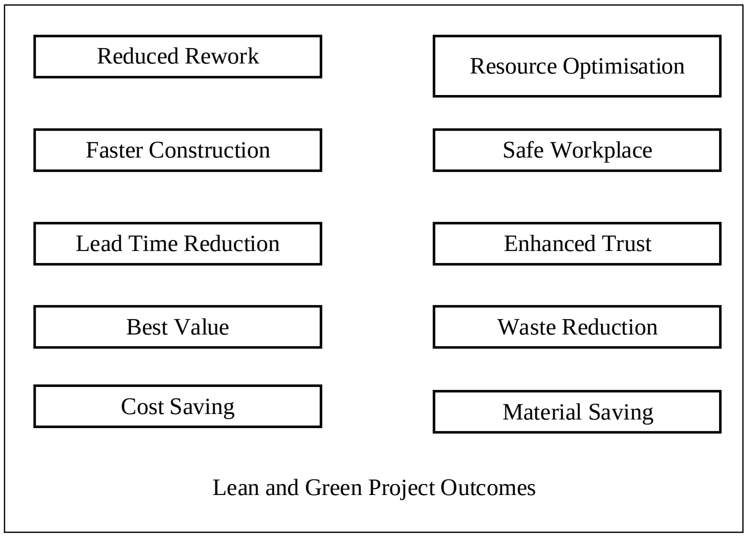


Figure 4: Lean and green project outcomes

Development of BIM-based organizational capabilities framework

Using the concept of operational innovation, we have developed a framework for BIM-based organizational capabilities needed for effective BIM usage within organizations for attaining lean and green project outcomes. At the core of this development is the model proposed by Ulrich and Smallwood (2004) that links individual capabilities of employees to the organizational capabilities. This model has been modified in the context of BIM and its utilization to achieve lean and green outcomes. The technical skills of an individual in the organization were first categorized as their technical expertise to perform different BIM functions. Their expertise in different BIM functions helps the organization develop its BIM capabilities (listed in Table 2 and shown in Figure 1).

According to Ulrich & Smallwood (2004), organizational capabilities are key intangible assets and emerge when a company delivers on the combined competencies and abilities of its individuals. This has been explained with the help of an organizational capabilities matrix where the individual and organizational levels of analysis are combined along the technical and social skill set as shown in Figure 5. In this figure, the individual-technical layer (1) represents an individual's technical expertise for using various BIM functions. The individual–social layer (2) refers to an individual's leadership ability to communicate and motivate team members for using BIM functions. The organizational-technical layer (3) comprises of an organization's core technical competencies emphasising that an organization should know how to use the technical expertise and manage BIM implementation. The organizational-social layer (4) represents an organization's culture which enables the organization to turn its technical BIM know-how into desired project outcomes.

Capabilities			
	Technical	**1** An Individual's functional competence and expertise to use native BIM functions	Indivdual
	Social	**2** An individual's leadership ability to communicate within the team and motivate people to use BIM	
	Technical	**3** An organization's core technical competencies: A company must know how to utilize native BIM functions and develop BIM capabilities	Organisational
	Social	**4** An organization's BIM capabilities enable the organization to turn its technical know-how into desired lean and green outcomes	

Figure 5: Organizational capabilities matrix
[adapted from (Ulrich and Smallwood, 2004)]

Using this model of organizational capabilities development, a conceptual organizational capability framework as shown in Figure 6 was developed. The first layer of functions depicts the functional competence, technical skill set and expertise of a team member to use BIM. Using leadership (and other social) qualities of individuals, called social skill set in this framework, an individual spearheads, motivates and encourages others in the team and the organization to adopt BIM. Seeing operational innovation as a step change, the organization as a whole develops BIM capabilities, referred to the organizational capability layer. This is a crucial layer where an organization develops its core technical competencies under the technical skill set. Subsequently, once the organization develops a culture for BIM implementation where everyone in the team accepts the advantages of using a model-centric approach in the organizations under the social skill sets, it is then that an organization completely overcomes any potential resistance to change and turns its technical know-how skills into the desired outcomes.

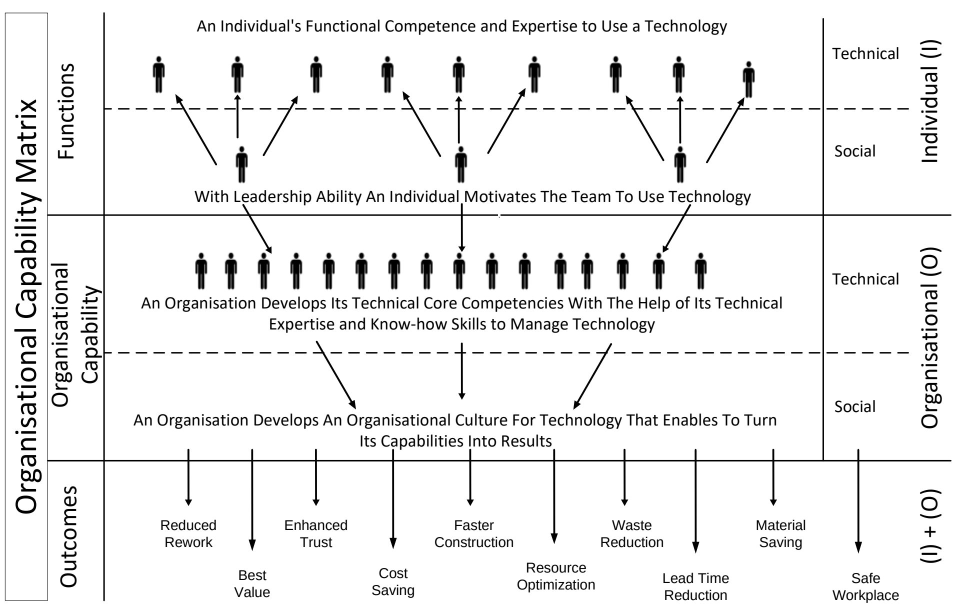


Figure 6: Conceptual organizational capability framework

On the basis of this conceptual framework a detailed framework for BIM-based organizational capabilities was developed. This detailed framework is shown in Figure 7. The hierarchical framework consists of the technology layer at the bottom – emphasizing the importance of an individual's expertise to use the thirty-three different native BIM functions. This layer is driven by the people of the organization and is not limited to an individual department but the leadership ability of the individuals helps in wider motivation, encouragement and acceptance of BIM usage amongst other teams and departments of the organization. Each BIM function along with other relevant BIM functions, thus helps an organization develop its organizational BIM capabilities. This is depicted in the second layer of the framework.

The second layer, is the process layer, where an organization develops its core technical competencies that lead to the BIM capabilities. The individual team members in the organization motivate each other and interact amongst themselves to explore various ways to use BIM process to develop the fifteen BIM capabilities for the organization. It is in this layer that a transition from the individual to the organization takes place where not only one individual, but the organization adopts and uses BIM. As the adoption rate of BIM in the organization increases and as people gain experience and become more familiar with the BIM capabilities, the organization ameliorates its know-how skills to manage BIM more efficiently.

Two key features are evident in the process layer of the detailed framework. First, the individual BIM capabilities are linked to the BIM functions that individually and collectively lead to the development of a particular capability (depicted in Figure 7 as a list of function numbers with each capability). Second, the process layer highlights the fact that the organization develops the fifteen capabilities in a hierarchical fashion. Therefore in the process layer the fifteen BIM capabilities are arranged under three categories: (1) independent capabilities; (2) linkage capabilities; and (3) dependent capabilities. This classification was developed by using the Interpretive Structural Modelling (ISM) (Warfield, 1974) and Cross Impact Matrix – Multiplication Applied to Classification (MICMAC) analysis (developed by J C Duperrin and M Godet in 1973 (Saxena et al., 1990)). These methods use the practical knowledge and experience of the industry experts to extract an overall structure, called digraph from complex set of factors on the basis of underlying relationships. It is an accepted methodology for generating solutions of complex problems, for identifying and understanding the direct and indirect relationships among specific items to analyse the influence between the elements (Malone, 1975). By using the ISM and MICMAC analysis the driving power and the dependence power of the BIM capabilities was determined (Ahuja, 2017). The experts were first asked individually to use a contextual relationship of "leads to" for linking the fifteen BIM capabilities. Four different choices were given to the experts: (1) BIM capability A helps to achieve BIM capability B; (2) BIM capability B helps to achieve BIM capability A; (3) BIM capability A helps to achieve BIM capability B and BIM capability B helps to achieve BIM capability A; and (4) BIM capabilities A and B have no relation between each other. After receiving individual inputs from the experts via semi-structured interviews, a focus groups was conducted in which the contextual relationships between the BIM capabilities were reconciled and consensus was obtained. This information was used to develop a Structural Self-interaction Matrix (SSIM) from which the Initial Reachability Matrix and the Final

Reachability Matrix were derived. Table 3 shows the final reachability matrix for the BIM capabilities.

Table 3: Final Reachability Matrix for BIM capabilities (list of capabilities from Table 2)

Capabilities	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	Driving Power
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	15
2	***1***	0	1	1	1	***1***	0	1	1	***1***	0	1	1	1	0	11
3	1	0	1	1	***1***	1	0	0	***1***	***1***	0	1	1	***1***	0	10
4	1	0	1	1	***1***	***1***	0	***1***	1	1	0	1	1	1	0	11
5	***1***	***1***	***1***	***1***	1	***1***	1	0	***1***	***1***	1	***1***	***1***	***1***	***1***	14
6	1	0	1	1	***1***	***1***	0	0	***1***	1	0	1	***1***	***1***	0	10
7	1	0	1	1	1	1	0	***1***	1	***1***	0	1	***1***	1	0	11
8	***1***	0	1	1	***1***	1	0	1	1	***1***	0	***1***	1	***1***	0	11
9	1	1	1	1	1	1	1	***1***	1	1	1	1	1	1	1	15
10	***1***	0	***1***	***1***	***1***	1	0	0	1	0	0	***1***	0	***1***	0	8
11	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
12	***1***	0	1	1	***1***	***1***	0	0	1	1	0	1	1	***1***	0	10
13	1	0	1	1	1	1	0	0	**1**	1	0	1	1	***1***	0	10
14	***1***	1	1	***1***	1	***1***	***1***	***1***	***1***	***1***	***1***	***1***	***1***	***1***	1	15
15	1	0	1	***1***	1	***1***	0	0	1	1	0	1	***1***	***1***	0	10
Dependence Power	14	4	14	14	15	14	4	7	14	13	4	14	13	14	4	

The Final Reachability Matrix provided the ‘Driving Power’ and ‘Dependence Power’ of each capability. The Driving Power of a BIM capability is the total number of capabilities (including itself) it helps achieve and the Dependence Power is the total number of capabilities (including itself) that help achieve it (Singh and Kant, 2008). On the basis of the ‘Driving Power’ and ‘Dependence Power’ of each capability MICMAC analysis was conducted to partition the BIM capabilities into: independent, linkage, dependent and autonomous capabilities (none of the BIM capabilities fell under this category) (Mandal and Deshmukh, 1994). Table 4 provides the categorisation of BIM capabilities.

Table 4: Categorisation of BIM capabilities using MICMAC analysis

Category	***BIM Capabilities***
Autonomous BIM capability (weak driving power and weak dependence)	-
Dependent BIM capability (weak driving power but strong dependence power)	Facilities management
Linkage BIM capability (high driving as well as high dependence power)	Design coordination, Prefabrication and modularisation, Construction scheduling and sequencing, Integrated site planning, Change management, Quantity take-off,

	Collaboration and coordination, and BIM for Supply chain management
Independent BIM capability (strong driving power but weak dependence power)	Visualization, Energy and environment analysis, Structural analysis, MEP system modelling, Constructability analysis, and BIM for as-built

Based on this analysis the process layer of the detailed framework provides the BIM capabilities in three hierarchical sub-layers (as shown in Figure 7). Based on the expert view captured via ISM and MICMAC analysis the identified independent BIM capabilities—Visualization, Energy and environment analysis, Structural analysis, MEP system modelling, Constructability analysis, and BIM for as-built—became the key focus of the framework. Table 4 was discussed with the experts in a final focus group session and it then emerged that Energy and environment analysis, Structural analysis, MEP system modelling, and Constructability analysis are the four main BIM capabilities that a design organization must focus on.

Finally, the top layer of the detailed framework has been termed as the 'outcomes layer' and is the result of an organization's knowledge regarding BIM usage and implementation and an underlying BIM adoption culture which helps the organization to turn its BIM capabilities into lean and green project outcomes.

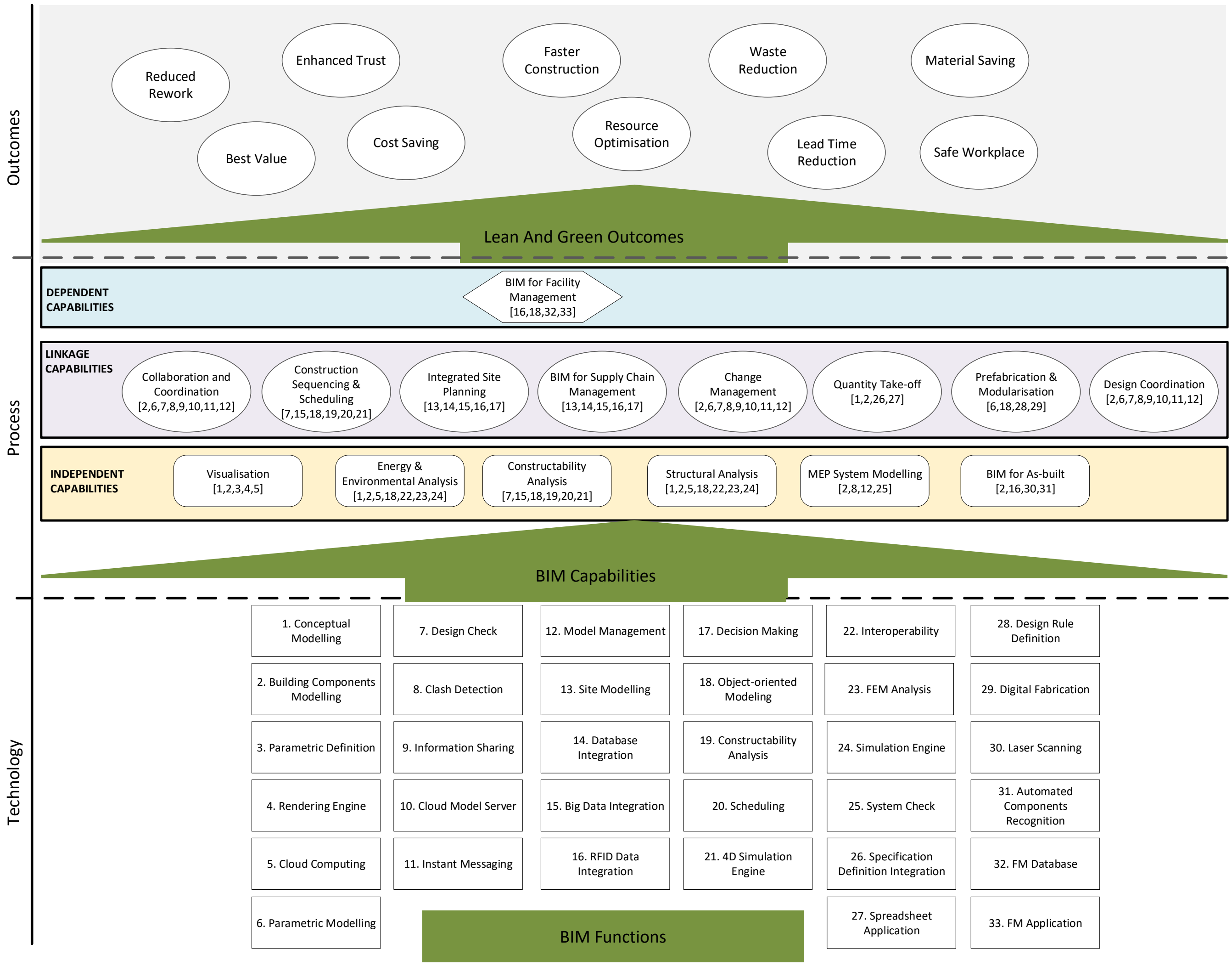


Figure 7: Framework for BIM-based organizational capabilities

Testing and Validation of the framework

The framework for BIM-based organizational capabilities that was developed by collating information from the literature, and via semi-structured interviews and focus groups of experts was tested and validated with the help of BIM case studies. Crisp set (csQCA) as proposed by Ragin (2013), was used for the testing and validation purposes. Four conditions (independent BIM capabilities of Energy and environment analysis (E&EA), Structural analysis (SA), MEP system modelling (MEP), and Constructability analysis (CA)), one outcome (attainment of lean and green project outcomes) and sixteen case studies were utilized for the csQCA. The data collection was done with the help of semi-structured interviews conducted with experts from design organizations. It involved various interview sessions and discussions with the BIM experts in these organizations. As a result, sixteen cases where various functions of BIM were used to attain lean and green project outcomes were examined. Table 5 provides a summary of the cases used in the csQCA analysis.

Table 5: Interpretive Data Matrix Table of 'Lean-Green outcome' and BIM capabilities (Ahuja *et al., 2017)*

Project Number	Type of Project	Conditions/Antecedents				Lean and Green Outcomes
		MEP	E&EA	CA	SA	
Project 1	Commercial	1	1	1	1	1
Project 2	Commercial	1	1	0	1	1
Project 3	Commercial	1	1	0	1	1
Project 4	Commercial	1	0	1	0	1
Project 5	Commercial	1	0	1	0	1
Project 6	Residential	1	0	1	1	1
Project 7	Residential	1	0	1	1	1
Project 8	Commercial	1	1	1	1	1
Project 9	Residential	1	0	0	0	0
Project 10	Commercial	1	0	0	0	0
Project 11	Residential	0	0	0	0	0
Project 12	Residential	1	1	1	1	1
Project 13	Residential	1	0	0	0	0
Project 14	Commercial	1	1	0	0	1
Project 15	Residential	1	1	0	0	1
Project 16	Residential	1	0	0	0	0

The csQCA analysis was setup with the outcome under study as a dichotomous variable: whether the organization achieved lean and green project outcome on a selected case study project. csQCA allows defining the threshold between absence and presence for each condition and the outcome theoretically based on case knowledge (Sehring et al., 2013). Therefore, for this research, the presence of five or more than five lean and green outcomes in a case was given the binary value of 1 and presence of four or less than four lean and green outcomes in a case were given the binary value of 0. Similarly the four conditions (selected four independent BIM capabilities) were also designed as dichotomous variables. Each condition was assigned a value of 1 if the organization possessed that capability or deployed it on the project, otherwise the condition was set to 0 signifying the lack of that capability. This information is summarized in Table 5 for the sixteen case study projects. From this table, the truth table that represents the relationships between the cases, conditions and outcomes was formed. Each row of the truth table represented one of the logically possible combinations of the conditions leading to the same outcome. The truth table sorted cases by the combinations of causal conditions they exhibited and allowed all logically possible combinations of conditions to be considered. This was generated with the help of a computer software, Tosmana 1.3.2.0 (Cronqvist, 2003) which is a useful tool for Small-N analysis. Using the information in the truth table the solution formula consisting of the outcome and the causal conditions leading to the outcome was developed. The formula uses three basic Boolean operators logical OR (+), logical AND (*), and logical NOT (where negation is denoted in csQCA by replacing an upper case letter with a lower case letter). The analysis revealed the following three sufficient antecedent combinations of BIM capabilities leading to lean and green outcomes (Ahuja et al., 2017):

MEP * E&EA* SA + MEP* E&EA*ca + MEP*e&ea*CA → L-G

The solution formula depicts that there are three sufficient paths leading to lean and green outcomes:

- use of MEP system modelling (MEP) AND use of energy and environment analysis (E&EA) at design stage AND performing structural analysis (SA) on construction projects
- OR use of MEP system modelling (MEP) AND use of energy and environment analysis (E&EA) at design stage AND absence of constructability analysis (ca)
- OR use of MEP system modelling (MEP) AND absence of use of energy and environment analysis (e&ea) AND use of constructability analysis (CA)

As per the csQCA analysis the solution set listed above presented a coverage and consistency of 1.00. Consequently, this solution explained a 100% possibility of obtaining lean and green results when organizations develop and deploy BIM capabilities on construction projects.

Discussion

This paper has identified a roadmap for generation of lean and green impact on construction projects through the use of BIM. The first step is for an individual in an organization who is familiar with BIM and its functionality to take the lead and act as a champion within the organization promoting it, encouraging colleagues, and trying to embed this day to day processes and steps within a construction project. It is through this champion that BIM will be adopted organization-wide. The champion needs to have good leadership, communication and motivational skills to promote BIM and encourage colleagues to adopt it. Indeed, the position of the individual within the organization will also play a key role towards the eventual successful adoption of BIM. Once the organization decides to adopt BIM then the next consideration is regarding the range of functions and what functions need to be implemented based on the nature of business of the organization. The choice of BIM functions will lead to development of processes and organizational capabilities. The capabilities such as visualisation, energy and environmental analysis, constructability analysis, structural analysis, MEP system modelling and BIM for as-built are some independent capabilities that an organization acquires. Most of these capabilities are applied at design stage thus embedding lean and green firmly in the project right from inception. Once most of the analysis and a range of "what if" scenarios are analysed, then only the design is taken forward to the construction stage. Capabilities such as better coordination and control, project management sequencing and scheduling, site planning, supply chain management, change management, quantity take-off, decisions on use of prefabrication and design coordination are linkage capabilities which ensure that the initial list of analysis to be conducted are firmly embedded in construction process and project. It is envisioned that eventually all these capabilities lead to lean and green outcomes such as reduction of work content, generation of better value, enhancement of value within the project team, cost savings, faster construction, optimal utilisation of resources, waste reduction, lead time reduction, material savings and safety in construction.

This paper has traced the path of realisation of lean and green outcomes from inception where one individual starts leading the BIM implementation within an organization all the way to the realization of lean and green outcomes which will reflect in project outcomes and will result in benefits for all stakeholders of the project. One of the key contributions of this paper is the tracing of the path from inception to realization of benefits clearly highlighting steps and processes involved at different stages. Additionally, the paper has developed a framework for BIM-based organizational capabilities leading to realization of lean and green benefits.

Conclusions

Through the findings and research of this paper, it can be seen that an organization needs to develop individual and collective capabilities to use BIM as a lever to create a shift of an increase of lean and green outcomes. The major theoretical contribution of this study is towards the development of a framework for BIM-based organizational capabilities, which demonstrates the possibility of achieving lean and green outcomes by adopting a BIM culture. The framework is quite comprehensive and clearly identifies the sequence of steps needed to achieve successful lean and green outcomes through the implementation of BIM. The steps highlighted present a roadmap for organizations to follow and realize benefits for all the stakeholders within the project. The suggested framework for BIM-based organizational capabilities is a tool that can potentially be administered by the national level bodies for rating construction organizations for BIM adoption in building projects. Additionally, the framework will help AEC organizations to plan effective implementation of BIM to achieve lean and green outcomes with the help of the social and technical skill sets available from the different people and process levels within the organizations. Ultimately, it can be said that by implementing this framework and by implementing the concept of BIM itself, AEC organizations would be able to compete on a universal platform.

References

Abanda, F.H. and Byers, L. (2016), "An investigation of the impact of building orientation on energy consumption in a domestic building using emerging BIM (Building Information Modelling)", *Energy,* Vol. 97, pp. 517–527.

Abanda, F.H., Tah, J.H.M. and Cheung, F.K.T. (2017), "BIM in off-site manufacturing for buildings", *Journal of Building Engineering,* Vol. 14, pp. 89–102.

Ahankoob, A., Khoshnava, S.M., Rostami, R. and Preece, C. (2012), "BIM perspectives on construction waste reduction", *Management in Construction Research Association,* pp. 195–199.

Ahuja, R. (2017), *Investigating the Role of BIM in Promoting Lean and Green Outcomes on Construction Projects,* Amity University.

Ahuja, R., Sawhney, A. and Arif, M. (2017), "Driving lean and green project outcomes using BIM: A qualitative comparative analysis", *International Journal of Sustainable Built Environment,* Vol. 6 No. 1, pp. 69–80.

Ajayi, S.O., Oyedele, L.O., Ceranic, B., Gallanagh, M. and Kadiri, K.O. (2015), "Life cycle environmental performance of material specification: a BIM-enhanced comparative assessment", *International Journal of Sustainable Building Technology and Urban Development,* Vol. 6 No. 1, pp. 14–24.

Alarcón, L.F., Diethelm, S., Rojo, O. and Calderon, R. (2005), "Assessing the impacts of implementing lean construction", *13th International Group for Lean Construction Conference, IGLC 13, July 19, 2005 - July 21, 2005,* pp. 387–393.

Alirezaei, M., Noori, M., Tatari, O., Mackie, K.R. and Elgamal, A. (2016), "BIM-based Damage Estimation of Buildings under Earthquake Loading Condition", *Procedia Engineering,* Vol. 145, pp. 1051–1058.

Alwan, Z., Greenwood, D. and Gledson, B. (2015), "Rapid LEED evaluation performed with BIM based sustainability analysis on a virtual construction project", *Construction Innovation,* Vol. 15 No. 2, pp. 134–150.

Amit, R. and Schoemaker, P.J.H. (1993), "Strategic assets and organizational rent", *Strategic Management Journal,* Vol. 14 No. 1, pp. 33–46.

Aram, S., Eastman, C. and Sacks, R. (2013), "Requirements for BIM platforms in the concrete reinforcement supply chain", *Automation in Construction,* Elsevier B.V., Vol. 35, pp. 1–17.

Arayici, Y., Egbu, C. and Coates, P. (2012), "Building information modelling (BIM) implementation and remote construction projects: Issues, challenges, and critiques", *Electronic Journal of Information Technology in Construction*.

Azhar, S. and Brown, J. (2009), "BIM for Sustainability Analyses", *International Journal of Construction Education and Research,* Vol. 5 No. 4, pp. 276–292.

Azhar, S., Carlton, W. a., Olsen, D. and Ahmad, I. (2011), "Building information modeling for sustainable design and LEED® rating analysis", *Automation in Construction,* Elsevier B.V., Vol. 20 No. 2, pp. 217–224.

Azhar, S., Nadeem, A., Mok, J.Y.. and Leung, B.H.Y. (2008), “Building Information Modeling (BIM): A New Paradigm for Visual Interactive Modeling and Simulation for Construction Projects”, *International Conference on Construction in Developing Counties (ICCIDIC)*, Vol. 1.

Babič, N.Č., Podbreznik, P. and Rebolj, D. (2010), “Integrating resource production and construction using BIM”, *Automation in Construction*, Vol. 19 No. 5, pp. 539–543.

Bae, J. and Kim, Y. (2008), “Sustainable Value on Construction Projects and Lean Construction”, *Journal of Green Building*, Vol. 3 No. 1, pp. 156–167.

Barnes, S. and Castro-Lacouture, D. (2009), “BIM-Enabled Integrated Optimization Tool for LEED Decisions”, *Computing in Civil Engineering (2009)*, American Society of Civil Engineers, Reston, VA, pp. 258–268.

Beach, T., Petri, I., Rezgui, Y. and Rana, O. (2017), “Management of Collaborative BIM Data by Federating Distributed BIM Models”, *Journal of Computing in Civil Engineering*, Vol. 31 No. 4, p. 4017009.

Becerik-Gerber, B. and Rice, S. (2010), “The perceived value of building information modeling in the US building industry”, *Journal of Information Technology in Construction*, Vol. 15 No. February, pp. 185–201.

BorjeGhaleh, R.M. and Sardroud, J.M. (2016), “Approaching Industrialization of Buildings and Integrated Construction Using Building Information Modeling”, *Procedia Engineering*, Vol. 164, pp. 534–541.

Bosché, F., Guillemet, A., Turkan, Y., Haas, C.T. and Haas, R. (2014), “Tracking the Built Status of MEP Works: Assessing the Value of a Scan-vs-BIM System”, *Journal of Computing in Civil Engineering*, Vol. 28 No. 4, p. 5014004.

Boton, C., Kubicki, S. and Halin, G. (2015), “The Challenge of Level of Development in 4D/BIM Simulation Across AEC Project Lifecyle. A Case Study”, *Procedia Engineering*, Vol. 123, pp. 59–67.

Cabaleiro, M., Riveiro, B., Arias, P., Caamaño, J.C. and Vilán, J.A. (2014), “Automatic 3D modelling of metal frame connections from LiDAR data for structural engineering purposes”, *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 96, pp. 47–56.

Cemal, Z., Acar, a Z. and Haluk, T. (2006), “Identifying Organizational Capabilities As Predictors of Growth and Business Performance”, *The Business Review, Cambridge*, Vol. 5 No. 2, pp. 109–116.

Chen, L. and Fong, P.S.W. (2013), “Visualizing Evolution of Knowledge Management Capability in Construction Firms”, *Journal of Construction Engineering and Management*, Vol. 139 No. 7, pp. 839–851.

Chen, Y.J., Feng, C.W. and Lee, K.W. (2012), “The Application of BIM Model in M/E/P Construction Coordination”, *Applied Mechanics and Materials*, Vol. 229–231, pp. 2760–2764.

Chi, H.-L., Wang, X. and Jiao, Y. (2015), “BIM-Enabled Structural Design: Impacts and Future Developments in Structural Modelling, Analysis and Optimisation Processes”, *Archives of Computational Methods in Engineering*, Vol. 22 No. 1, pp. 135–151.

Choi, J., Kim, H. and Kim, I. (2015), “Open BIM-based quantity take-off system for schematic estimation of building frame in early design stage”, *Journal of Computational Design and Engineering*, Vol. 2 No. 1, pp. 16–25.

Ciribini, A.L.C., Mastrolembo Ventura, S. and Paneroni, M. (2016), “Implementation of an interoperable process to optimise design and construction phases of a residential building: A BIM Pilot Project”, *Automation in Construction*, Vol. 71, pp. 62–73.

Collis, D.J. (1994), “Research Note: How Valuable are Organizational Capabilities?”, *Strategic Management Journal*, Vol. 15 No. S1, pp. 143–152.

Cone, K. (2013), “Sustainability + BIM + integration, a symbiotic relationship”, *AIA*, available at: www.aia.org/practicing/groups/kc/AIAB081071 (accessed 20 June 2016).

Cory, C.A. (2015), “New Visualization Techniques in AEC-BIM More than Modeling”, *The Visual Language of Technique*, Springer International Publishing, Cham, pp. 49–64.

Cronqvist, L. (2003), “Presentation of TOSMANA Adding Multi-Value Variables and Visual Aids to QCA”, *COMPASSS Launching Conference*, Louvain-La-Neuve and Leuven.

Dave, B., Koskela, P.L. and Kiviniemi, P.A. (2013), *Implementing Lean in Construction: Lean Construction and BIM*, CIRIA, London.

Davies, A. and Brady, T. (2016), “Explicating the dynamics of project capabilities”, *International Journal of Project Management*, Vol. 34 No. 2, pp. 314–327.

Ding, L., Zhou, Y. and Akinci, B. (2014), “Building Information Modeling (BIM) application framework: The process of expanding from 3D to computable nD”, *Automation in Construction*, Vol. 46, pp. 82–93.

Dore, C. and Murphy, M. (2014), “Semi-automatic generation of as-built BIM façade geometry from laser and image data”, *Journal of Information Technology in Construction*, Vol. 19, pp. 20–46.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K. (2011), *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, Second Edi., Wiley.

Faghihi, V., Reinschmidt, K.F. and Kang, J.H. (2014), “Construction scheduling using Genetic Algorithm based on Building Information Model”, *Expert Systems with Applications*, Vol. 41 No. 16, pp. 7565–7578.

Forgues, D., Staub-French, S., Tahrani, S. and Poirier, E. (2014), *The Inevitable Shift Towards Building Information Modelling (BIM) in Canada’s Construction Sector: A Three-Project Summary, CEFRIO: The Digital Experience*, available at:https://doi.org/10.13140/RG.2.1.1850.8645.

Formoso, C.T., Soibelman, L., De Cesare, C. and Isatto, E.L. (2002), “Material Waste in

Building Industry: Main Causes and Prevention", *Journal of Construction Engineering and Management*, Vol. 128 No. 4, pp. 316–325.

Gerber, D.J., Becerik-Gerber, B. and Kunz, A. (2010), "Building Information Modeling and Lean Construction: Technology, Methodology and Advances from Practice", *18th Annual Conference, International Group for Lean Construction*, Haifa, Israel, pp. 1–11.

Gijezen, S., Hartmann, T. and Buursema, N. (2009), "Organizing 3D Building Information Models With the Help of Work Breakdown Structures To Improve the Clash Detection Process", Netherlands, pp. 1–30.

Golparvar-Fard, M., Peña-Mora, F. and Savarese, S. (2011), "Integrated Sequential As-Built and As-Planned Representation with D4AR Tools in Support of Decision-Making Tasks in the AEC/FM Industry", *Journal of Construction Engineering and Management*, Vol. 137 No. 12, pp. 1099–1116.

Gourlis, G. and Kovacic, I. (2017), "Building Information Modelling for analysis of energy efficient industrial buildings – A case study", *Renewable and Sustainable Energy Reviews*, Vol. 68, pp. 953–963.

Grilo, A. and Jardim-Goncalves, R. (2011), "Challenging electronic procurement in the AEC sector: A BIM-based integrated perspective", *Automation in Construction*, Vol. 20 No. 2, pp. 107–114.

Hamdi, O. and Leite, F. (2012), "BIM and Lean interactions from the BIM capability maturity model perspective: A case study", *IGLC 2012 - 20th Conference of the International Group for Lean Construction*.

Hammer, M. (2004), "Deep change - how operational innovation can transform your company", *IEEE Engineering Management Review*, Vol. 32 No. 3, pp. 42–42.

Hartmann, V., Beucke, K.E., Shapir, K. and König, M. (2012), "Model-based Scheduling for Construction Planning", *14th International Conference on Computing in Civil and Building Engineering*.

Hill, R.C. and Bowen, P.A. (1997), "Sustainable construction: principles and a framework for attainment", *Construction Management and Economics*, Vol. 15 No. 3, pp. 223–239.

Hooper, M. and Ekholm, A. (2010), "A pilot study: Towards BIM integration - An analysis of design information exchange & coordination", *CIB W78: 27th International Conference*, pp. 16–18.

Hu, Z.-Z., Zhang, J.-P., Yu, F.-Q., Tian, P.-L. and Xiang, X.-S. (2016), "Construction and facility management of large MEP projects using a multi-Scale building information model", *Advances in Engineering Software*, Vol. 100, pp. 215–230.

Irizarry, J., Karan, E.P. and Jalaei, F. (2013), "Integrating BIM and GIS to improve the visual monitoring of construction supply chain management", *Automation in Construction*, Vol. 31, pp. 241–254.

Jiang, L., Leicht, R.M. and Okudan Kremer, G.E. (2014), "Eliciting Constructability Knowledge for BIM-enabled Automated, Rule-based Constructability Review: A Case Study of

Formwork”, *Construction Research Congress 2014*, American Society of Civil Engineers, Reston, VA, VA, pp. 319–328.

Johansson, M., Roupé, M. and Bosch-Sijtsema, P. (2015), “Real-time visualization of building information models (BIM)”, *Automation in Construction*, Vol. 54, pp. 69–82.

Johansson, P., Linderoth, H.C.J. and Granth, K. (2014), “The role of BIM in preventing design errors”, *30th Annual Association of Researchers in Construction Management Conference, ARCOM, September 1 - 3, Portsmouth, UK*, pp. 703–712.

Jun-Qing, X.U. and Hui-Min, L.U. (2011), “Information Flow Model for Construction Supply Chain Based on BIM”, *Journal of Engineering Management*, Vol. 2 No. 5.

Jung, J., Hong, S., Jeong, S., Kim, S., Cho, H., Hong, S. and Heo, J. (2014), “Productive modeling for development of as-built BIM of existing indoor structures”, *Automation in Construction*, Vol. 42, pp. 68–77.

Kang, T.W. and Hong, C.H. (2015), “A study on software architecture for effective BIM/GIS-based facility management data integration”, *Automation in Construction*, Vol. 54, pp. 25–38.

Kannan, M.R. and Santhi, M.H. (2013), “Constructability Assessment of Climbing Formwork Systems Using Building Information Modeling”, *Procedia Engineering*, Vol. 64, pp. 1129–1138.

Karan, E.P. and Irizarry, J. (2015), “Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services”, *Automation in Construction*, Vol. 53, pp. 1–12.

Kassem, M., Kelly, G., Dawood, N., Serginson, M. and Lockley, S. (2015), “BIM in facilities management applications: a case study of a large university complex”, edited by E.D. Love, Jane Matthews and Steve, P.*Built Environment Project and Asset Management*, Vol. 5 No. 3, pp. 261–277.

Khalfan, M., Khan, H. and Maqsood, T. (2015), “Building Information Model and Supply Chain Integration: A Review”, *Journal of Economics, Business and Management*, Vol. 3 No. 9, available at:https://doi.org/10.7763/JOEBM.2015.V3.308.

Khanzode, A., Fischer, M. and Dean, R. (2008), “Benefits and lessons learned of implementing building Virtual Design and Construction (VDC) technologies for coordination of Mechanical, Electrical, and Plumbing (MEP) systems on a large healthcare project”, *Electronic Journal of Information Technology in Construction*, Vol. 13 No. September 2007, pp. 324–342.

Kifokeris, D. and Xenidis, Y. (2017), “Constructability: Outline of Past, Present, and Future Research”, *Journal of Construction Engineering and Management*, Vol. 143 No. 8, p. 4017035.

Kim, K., Cho, Y. and Zhang, S. (2016), “Integrating work sequences and temporary structures into safety planning: Automated scaffolding-related safety hazard identification and prevention in BIM”, *Automation in Construction*, Vol. 70, pp. 128–142.

Konig, M., Habenicht, I., Bochum, R.-U. and AG, S. (2012), “Intelligent BIM based construction scheduling using discrete event simulation”, *Winter Simulation Conference*, pp. 662–673.

Koranda, C., Chong, W.K., Kim, C., Chou, J.-S. and Kim, C. (2012), “An investigation of the applicability of sustainability and lean concepts to small construction projects”, *KSCE Journal of Civil Engineering*, Vol. 16 No. 5, pp. 699–707.

Koskela, L., Owen, R. and Dave, B. (2010), “Lean construction, building information modelling and sustainability”, *Eracobuild Workshop, Malmö, Sweden*, Vol. 44, pp. 1–8.

Krygiel, E. and Nies, B. (2008), *Green BIM: Successful Sustainable Design with Building Information Modeling*, John Wiley & Sons.

Kumar, S.S. and Cheng, J.C.P. (2015), “A BIM-based automated site layout planning framework for congested construction sites”, *Automation in Construction*, Vol. 59 No. November 2015, pp. 24–37.

Kumaraswamy, M. and Dulaimi, M. (2001), “Empowering innovative improvements through creative construction procurement”, *Engineering, Construction and Architectural Management*, Vol. 8 No. 5/6, pp. 325–334.

Langroodi, B.P. and Staub-French, S. (2012), “Change Management with Building Information Models: A Case Study”, *Construction Research Congress 2012*, American Society of Civil Engineers, Reston, VA, pp. 1182–1191.

Lee, H.W., Oh, H., Kim, Y. and Choi, K. (2015), “Quantitative analysis of warnings in building information modeling (BIM)”, *Automation in Construction*, Vol. 51, pp. 23–31.

Lee, S.-I., Bae, J.-S. and Cho, Y.S. (2012), “Efficiency analysis of Set-based Design with structural building information modeling (S-BIM) on high-rise building structures”, *Automation in Construction*, Vol. 23, pp. 20–32.

Lee, S.-K., Kim, K.-R. and Yu, J.-H. (2014), “BIM and ontology-based approach for building cost estimation”, *Automation in Construction*, Elsevier B.V., Vol. 41, pp. 96–105.

Liu, F., Jallow, A.K., Anumba, C.J. and Wu, D. (2014), “A Framework for Integrating Change Management with Building Information Modeling”, *Computing in Civil and Building Engineering (2014)*, American Society of Civil Engineers, Reston, VA, pp. 439–446.

Liu, H., Lu, M. and Al-Hussein, M. (2016), “Ontology-based semantic approach for construction-oriented quantity take-off from BIM models in the light-frame building industry”, *Advanced Engineering Informatics*, Vol. 30 No. 2, pp. 190–207.

Liu, R. and Issa, R.R.A. (2013), “Issues in BIM for Facility Management from Industry Practitioners’ Perspectives”, *Computing in Civil Engineering*, American Society of Civil Engineers, Reston, VA, VA, pp. 411–418.

Liu, Y., van Nederveen, S. and Hertogh, M. (2017), “Understanding effects of BIM on collaborative design and construction: An empirical study in China”, *International Journal of Project Management*, Vol. 35 No. 4, pp. 686–698.

Loufrani-Fedida, S. and Missonier, S. (2015), “The project manager cannot be a hero anymore!

Understanding critical competencies in project-based organizations from a multilevel approach”, *International Journal of Project Management*, Vol. 33 No. 6, pp. 1220–1235.

Lu, Q., Won, J. and Cheng, J.C.P. (2016), “A financial decision making framework for construction projects based on 5D Building Information Modeling (BIM)”, *International Journal of Project Management*, Vol. 34 No. 1, pp. 3–21.

Ma, Z. and Ma, J. (2017), “Formulating the application functional requirements of a BIM-based collaboration platform to support IPD projects”, *KSCE Journal of Civil Engineering*, Vol. 21 No. 6, pp. 2011–2026.

Ma, Z., Shen, Q. and Zhang, J. (2005), “Application of 4D for dynamic site layout and management of construction projects”, *Automation in Construction*, Vol. 14 No. 3, pp. 369–381.

Mahalingam, A., Yadav, A.K. and Varaprasad, J. (2015), “Investigating the Role of Lean Practices in Enabling BIM Adoption: Evidence from Two Indian Cases”, *Journal of Construction Engineering and Management*, Vol. 141 No. 7, p. 5015006.

Malone, D.W. (1975), “An introduction to the application of interpretive structural modeling”, *Proceedings of the IEEE*, Vol. 63 No. 3, pp. 397–404.

Mandal, A. and Deshmukh, S.G. (1994), “Vendor Selection Using Interpretive Structural Modelling (ISM)”, *International Journal of Operations & Production Management*, Vol. 14 No. 6, pp. 52–59.

Maylor, H., Vidgen, R. and Carver, S. (2008), “Managerial complexity in project-based operations: A grounded model and its implications for practice”, *Project Management Journal*, Vol. 39 No. S1, pp. S15–S26.

Mckinsey & Company. (2010), “Building organizational capabilities: McKinsey Global survey results”, No. March, pp. 1–10.

Mignone, G., Hosseini, M.R., Chileshe, N. and Arashpour, M. (2016), “Enhancing collaboration in BIM-based construction networks through organisational discontinuity theory: a case study of the new Royal Adelaide Hospital”, *Architectural Engineering and Design Management*, Vol. 12 No. 5, pp. 333–352.

Monteiro, A. and Poças Martins, J. (2013), “A survey on modeling guidelines for quantity takeoff-oriented BIM-based design”, *Automation in Construction*, Elsevier B.V., Vol. 35 No. November 2013, pp. 238–253.

Ogunbiyi, O., Oladapo, A. and Goulding, J. (2014), “An empirical study of the impact of lean construction techniques on sustainable construction in the UK”, *Construction Innovation: Information, Process, Management*, Vol. 14 No. 1, pp. 88–107.

Oskouie, P., Gerber, D., Alves, T. and Becerik-Gerber, B. (2012), “Extending the Interaction of Building Information Modeling and Lean Construction”, *20th Conference of the International Group for Lean Construction*, Vol. 1 No. 617, pp. 111–120.

Papadonikolaki, E. and Wamelink, H. (2017), “Inter- and intra-organizational conditions for supply chain integration with BIM”, *Building Research & Information*, Vol. 45 No. 6, pp.

649–664.

Park, J. and Cai, H. (2017), “WBS-based dynamic multi-dimensional BIM database for total construction as-built documentation”, *Automation in Construction*, Vol. 77, pp. 15–23.

Pătrăucean, V., Armeni, I., Nahangi, M., Yeung, J., Brilakis, I. and Haas, C. (2015), “State of research in automatic as-built modelling”, *Advanced Engineering Informatics*, Vol. 29 No. 2, pp. 162–171.

Peng, W. and Pheng, L.S. (2011), “Lean and green: emerging issues in the construction industry – a case study”, *20-21 Sep 2011, EPPM, Singapore*, pp. 20–21.

Pilehchian, B., Staub-French, S. and Nepal, M.P. (2015), “A conceptual approach to track design changes within a multi-disciplinary building information modeling environment”, *Canadian Journal of Civil Engineering*, Vol. 42 No. 2, pp. 139–152.

Pittet, P., Cruz, C. and Nicolle, C. (2014), “An ontology change management approach for facility management”, *Computers in Industry*, Vol. 65 No. 9, pp. 1301–1315.

Ragin, C.C. (2013), *The Comparative Method: Moving Beyond Qualitative and Quantitative Strategies*, University of California Press, Berkeley.

Rahman, A., Gonzalez, V.A. and Amor, R. (2013), “Exploring the Synergies Between BIM and Lean Construction To Deliver Highly Integrated Sustainable Projects”, *Proceedings of AUBEA, Aukland, New Zealand*, No. 20–22 N0vember, pp. 1–12.

Ramaji, I.J. and Memari, A.M. (2015), “Information Exchange Standardization for BIM Application to Multi-Story Modular Residential Buildings”, *AEI 2015*, American Society of Civil Engineers, Reston, VA, VA, pp. 13–24.

Sacks, R., Koskela, L., Dave, B.A. and Owen, R. (2010), “Interaction of Lean and Building Information Modeling in Construction”, *Journal of Construction Engineering and Management*, Vol. 136 No. 9, pp. 968–980.

Sacks, R., Radosavljevic, M. and Barak, R. (2010), “Requirements for building information modeling based lean production management systems for construction”, *Automation in Construction*, Vol. 19 No. 5, pp. 641–655.

Sawhney, A., Agnihotri, R. and Kumar Paul, V. (2014), “Grand challenges for the Indian construction industry”, edited by Florence Yean Yng Ling and Dr Carlo, D.*Built Environment Project and Asset Management*, Vol. 4 No. 4, pp. 317–334.

Sawhney, A., Khanzode, A.R. and Tiwari, S. (2017), *Building Information Modelling for Project Managers, RICS Insight Paper*.

Saxena, J.P., Sushil and Vrat, P. (1990), “Impact of indirect relationships in classification of variables-a micmac analysis for energy conservation”, *Systems Research*, Vol. 7 No. 4, pp. 245–253.

Schlueter, A. and Thesseling, F. (2009), “Building information model based energy/exergy performance assessment in early design stages”, *Automation in Construction*, Vol. 18 No. 2, pp. 153–163.

Seeam, A., Zheng, T., Lu, Y., Usmani, A. and Laurenson, D. (2013), “BIM Integrated Workflow Management and Monitoring System for Modular Buildings”, *International Journal of 3-D Information Modeling*, Vol. 2 No. 1, pp. 17–28.

Sehring, J., Korhonen-Kurki and Brockhaus, M. (2013), *Qualitative Comparative Analysis (QCA): An Application to Compare National REDD+ Policy Processes*, No. 21, available at:https://doi.org/10.17528/cifor/004278.

Selçuk Çıdık, M., Boyd, D. and Thurairajah, N. (2017), “Innovative Capability of Building Information Modeling in Construction Design”, *Journal of Construction Engineering and Management*, Vol. 143 No. 8, p. 4017047.

Shadram, F., Johansson, T.D., Lu, W., Schade, J. and Olofsson, T. (2016), “An integrated BIM-based framework for minimizing embodied energy during building design”, *Energy and Buildings*, Vol. 128, pp. 592–604.

Shi, Y., Du, J., Lavy, S. and Zhao, D. (2016), “A Multiuser Shared Virtual Environment for Facility Management”, *Procedia Engineering*, Vol. 145, pp. 120–127.

Shrivastava, A., Chaurasia, D. and Saxena, S. (2017), “Parameters for Assessing a Building Project Within the Purview of Constructability”, pp. 1209–1214.

Shrivastava, S. and Chini, A. (2012), “Using Building Information Modeling to Assess the Initial Embodied Energy of a Building”, *International Journal of Construction Management*, Vol. 12 No. 1, pp. 51–63.

Singh, M.D. and Kant, R. (2008), “Knowledge management barriers: An interpretive structural modeling approach”, *UK International Journal of Management Science and Engineering Management*, Vol. 3 No. 2, pp. 141–150.

Singh, M.M., Sawhney, A. and Borrmann, A. (2017), “Integrating rules of modular coordination to improve model authoring in BIM”, *International Journal of Construction Management*, Taylor & Francis, Vol. 0 No. 0, pp. 1–17.

Tauriainen, M., Puttonen, J., Saari, A., Laakso, P. and Forsblom, K. (2015), “The assessment of constructibility: BIM cases”, *Ecppm*, Vol. 20 No. October 2014, pp. 55–61.

Too, E.G. (2012), “Capability Model to Improve Infrastructure Asset Performance”, *Journal of Construction Engineering and Management*, Vol. 138 No. 7, pp. 885–896.

Ulrich, D. and Smallwood, N. (2004), “Capitalizing on capabilities”, *Harvard Business Review*, Vol. 82 No. 6, pp. 1–10.

Wang, J., Wang, X., Shou, W., Chong, H.-Y. and Guo, J. (2016), “Building information modeling-based integration of MEP layout designs and constructability”, *Automation in Construction*, Vol. 61, pp. 134–146.

Wang, J., Wang, X., Shou, W. and Xu, B. (2014), “Integrating BIM and augmented reality for interactive architectural visualisation”, edited by Pour Rahimian, F. and Ibrahim, R.*Construction Innovation*, Vol. 14 No. 4, pp. 453–476.

Wang, L. and Leite, F. (2016), “Formalized knowledge representation for spatial conflict coordination of mechanical, electrical and plumbing (MEP) systems in new building projects", *Automation in Construction*, Vol. 64, pp. 20–26.

Wang, W.-C., Weng, S.-W., Wang, S.-H. and Chen, C.-Y. (2014), "Integrating building information models with construction process simulations for project scheduling support", *Automation in Construction*, Vol. 37, pp. 68–80.

Warfield, J.N. (1974), "Developing Interconnection Matrices in Structural Modeling", *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. SMC-4 No. 1, pp. 81–87.

Wetzel, E.M. and Thabet, W.Y. (2015), "The use of a BIM-based framework to support safe facility management processes", *Automation in Construction*, Vol. 60, pp. 12–24.

Winter, S.G. (2003), "Understanding dynamic capabilities", *Strategic Management Journal*, Vol. 24 No. 10, pp. 991–995.

Wong, J.K.W. and Zhou, J. (2015), "Enhancing environmental sustainability over building life cycles through green BIM: A review", *Automation in Construction*, Vol. 57, pp. 156–165.

Woo, J., Wilsmann, J. and Kang, D. (2010), "Use of As-Built Building Information Modeling", *Construction Research Congress 2010*, American Society of Civil Engineers, Reston, VA, pp. 538–548.

Yalcinkaya, M. and Singh, V. (2015), "Patterns and trends in Building Information Modeling (BIM) research: A Latent Semantic Analysis", *Automation in Construction*, Vol. 59, pp. 68–80.

Yeoh, K.W. and Chua, D.K.H. (2014), "Representing Requirements of Construction from an IFC Model", *Computing in Civil and Building Engineering (2014)*, American Society of Civil Engineers, Reston, VA, VA, pp. 331–338.

Yung, P., Wang, J., Wang, X. and Jin, M. (2014), "A BIM-enabled MEP coordination process for use in China", *Journal of Information Technology in Construction*.

Zada, A.J., Tizani, W. and Oti, A.H. (2014), "Building Information Modelling (BIM)—Versioning for Collaborative Design", *Computing in Civil and Building Engineering (2014)*, American Society of Civil Engineers, Reston, VA, VA, pp. 512–519.

Zeibak-Shini, R., Sacks, R., Ma, L. and Filin, S. (2016), "Towards generation of as-damaged BIM models using laser-scanning and as-built BIM: First estimate of as-damaged locations of reinforced concrete frame members in masonry infill structures", *Advanced Engineering Informatics*, Vol. 30 No. 3, pp. 312–326.

Zhang, S., Teizer, J., Lee, J.-K., Eastman, C.M. and Venugopal, M. (2013), "Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules", *Automation in Construction*, Elsevier B.V., Vol. 29, pp. 183–195.