Driving Lean and Green Project Outcomes using BIM: A Qualitative Comparative Analysis

Abstract

Driven by a plethora of external and internal influences, the construction industry has independently embraced lean principles and green initiatives. Prima facie significant synergies have been reported between these two paradigms. It is foreseen that when tapped and adopted in unison, these paradigms may yield additional benefits for the construction projects. This synergy is investigated in this research. Further this study identifies and proposes Building Information Modelling (BIM) as an enabler for gaining lean and green project outcomes. The study uses crisp set qualitative comparative analysis (csQCA) method for exploring the causal combinations of different BIM capabilities and asserts that causal combinations of four BIM capabilities: MEP system modelling, energy and environment analysis, constructability analysis and structural analysis, when implemented on construction projects can lead to lean and green outcomes. With the help of sixteen cases it is shown that adoption of BIM leads to improved project outcomes especially ones targeting lean and green aspects.

Keywords

Building Information Modelling (BIM); lean; green; crisp set qualitative comparative analysis (csQCA); BIM capabilities, project outcomes

1 Introduction and Background

Today most of the construction work is carried out in the form of complex projects and hence, good project management practices are considered highly important (Maylor et al., 2008). Construction projects need to be expertly managed in terms of not only budgets and schedules, but also the quality and environmental impacts (Formoso et al., 2002; Howell and Ballard, 1998), as the construction industry is facing urgent pressure with regard to profitability, environmental management and sustainability (Planning Commission Government of India, 2013; Wang, 2014). Given the current conditions and the overall status of the sector, it is clear that business as usual is not tenable and hence, it is important that the industry embraces an agenda for change and continuous improvement. Inherent challenges such as excessive material and process waste, over reliance on resources, energy usage and carbon footprint are being addressed globally in order to meet the needs of the economy (WCED,1987; UNEP 2010). There is an urgent need to address the environmental challenges comprising of depletion and deterioration of natural resources to accelerate achievement of sustainable development goals (MoEF, 2011).

The built environment sector in particular is a major contributor of carbon emissions leading to climate change (Allu and Ebohon, 2015). For example, the construction sector in India accounts for nearly 24% of the total direct and indirect emissions of CO_2, and is the highest consumer of natural resources and energy in comparison to other sectors (Parikh et al., 2009). Energy efficiency and use of renewable energy; resource conservation; recycling; and minimization of waste are of utmost importance. The design, construction, operation and end-of-life processes embraced by the sector must continue to evolve for becoming highly efficient and sustainable. Not only is it important to deliver assets that are resource efficient and sustainable (through green principles) but also the delivery process must itself become highly efficient (through lean principles).

To deliver assets that are resource efficient and sustainable, the industry has embraced green principles. These principles, mostly used in the design stage of a project, allow project team members to create assets that are environmentally responsible and resource-efficient throughout the lifecycle of the asset. With low additional building cost, the adoption of passive design strategies and re-usable, recycled material into new construction helps to reduce the environmental impacts of building activities significantly (Chen et al., 2015; Coelho and de Brito, 2012). Certified green buildings decrease operating costs by 8 to 9 percent (Braham, 2007) with the productivity and health cost savings representing 70 percent of all savings in whole life cycle costs (Kats, 2003).

In the built environment sector a separate school of thought has emerged that focusses on eradicating the waste and inefficiencies that exist in the design and construction processes themselves. Encapsulated as the lean paradigm in construction, it strives to overcome the current challenges and inefficiencies in the project delivery process that are well understood and documented (Assaf & Al-Hejji, 2006; Ballard, 2000; KPMG, 2013; Odeh & Battaineh, 2002). The traditional project delivery system consisting of multiple tasks assigned to different agencies involved in a project, increases the likelihood of waste generation. This has also led to many problems such as cost overruns, schedule delays, poor quality, inadequate safety, disputes and litigation. With the lean construction movement, a new project delivery system called as Lean Project Delivery System (LPDS) was introduced as a method to reduce waste, to improve productivity and to maximize efficiency through all project phases including planning, design and construction (Ballard & Zabelle 2000).

Not realizing the inter-linkages between these two paradigms, the industry has very much progressed these two improvement agendas independently. This research investigated how green principles and lean principles are interlinked, determine benefits to projects when they are considered in a conjoint fashion and how they could be integrated into a single model. It is envisioned by the authors that combining lean and green methods is not only possible, but this also provides avenues to gain superior results on construction projects.

2 Problem Statement

Lean is a production management-based approach to project delivery (Howell and Ballard, 1999) which emphasizes on changing the traditional project delivery and work to minimize waste and to achieve maximum value. Similarly, green practices focus on energy efficiency and conservation of natural resources, thus encouraging the profound changes in concepts of design and management processes to reduce the overall environmental impact of buildings (Chau et al., 2010). The existing literature claims lean and green as compatible initiatives with their shared aim of waste identification, waste reduction, resource optimization and process improvement (Al-aomar and Weriakat, 2012; Bergmiller and Mccright, 2009; EPA, 2007). At the same time it is also reported that combined benefits of lean and green implementation can help to overcome the existing challenges faced by the construction industry. While the lean implementation leads to enhanced sustainability by reporting green benefits of shortened lead times, improved quality and reduced material waste (Luo et al., 2005); and reduced carbon emission and improved value chain (Peng and Pheng, 2011), the application of green principles in construction industry on the other hand, help to improve the cooperation and coordination among all parties involved in a project (Shen et al., 2007); cost saving on projects (Saggin et al., 2015); and minimization of waste throughout the lifecycle of construction projects (Yeheyis et al., 2013). Overall, although a fairly robust body of literature exists on the synergies and combined benefits of lean and green, there is still a gap in practice, with construction industry embracing both the initiatives separately (Ahuja et al., 2014; Bae and Kim, 2008; Sawhney and Ahuja, 2015). Additionally, limited research has been done to look at mechanisms that allow both, lean and green improvements on projects simultaneously.

3 BIM as a mechanism to achieve lean and green benefits

A study by Spence and Mulligan (1995) stated that nations must proceed towards sustainable development by embracing new technologies which are less resource-intensive and less environmentally damaging. Advanced information and communication technologies, and in particular Building Information Modelling (BIM) is playing a crucial role facilitating the development of green buildings (Zuo and Zhao, 2014). With a variety of software systems, BIM is transforming the way AEC projects are designed, engineered, built and managed (Autodesk, 2016; Eastman et al., 2008). Also, at the same time, it has been reported that BIM provides an effective platform for implementing lean principles (Mahalingam et al., 2015; Sacks et al., 2010). Although lean, green and BIM have their respective benefits and capabilities to address the problems faced by construction industry today, an amalgamation of these paradigms is now needed.

BIM is a technological innovation that can provide a platform for systemic improvement in the construction sector. The use of BIM throughout the lifecycle of built environment projects can enhance the lean and green benefits. In recent years, BIM is considered as one of the most valuable developments as it holds the potential to reduce efforts on production-oriented tasks and automate the unwanted tasks, thus increasing the process efficiency (Mahalingam et al., 2015). Various industry reports such as the Smart Market report (McGraw Hill Construction, 2009) have suggested that adoption of BIM leads to a wide range of lean benefits that includes improved productivity, enhanced quality, increased opportunities for new businesses and overall better project outcomes. Various researchers (Arayici et al., 2011; Nader et al., 2013; Navendren et al., 2014; Ramilo and Embi, 2014) underline that BIM adoption leads to efficiency gains, elimination of waste and value generation. The study by Dave et al. (2013) explains how BIM contributes directly to lean goals of waste reduction, improved flow and reduction in overall time with the application of clash detection, visualization and collaborative planning on projects. Simultaneously, many researchers have also asserted a strong relationship between BIM and green by confirming the green benefits achieved through BIM implementation on construction projects. A research by Azhar et al. (2010) showed that BIM helps in performing complex building performance analyses to ensure an optimized building design. The study by Love et al. (2011) depicted that BIM can significantly reduce the degree of rework and improve the performance of the projects. Furthermore, Bryde et al. (2013) stated cost reduction and control, significant time savings as the most frequent benefits of using BIM in construction industry. Motivated by this background, this research seeks to investigate the proposition that BIM promotes green and lean project outcomes in synergistic fashion.

4 Research Approach

The study adopts a qualitative research approach. Figure 1 shows the overall research framework adopted by the authors. This study explores the connection between BIM, lean and green. The research builds on the data resulting from semi-structured interviews and focus groups conducted with four architectural firms in India which are currently using BIM on their projects. Various questions pertaining to the lean and green benefit of BIM usage on projects were asked which were captured through note-taking on an excel sheet. The results of this analysis suggests that

MEP system modelling is critical antecedent for obtaining lean and green benefits. First, there is a discussion on the literature related to lean and green for identifying the project outcomes. Second, an overlap between the lean and green project outcomes is discussed. Third, the study identifies the conditions, outcomes and formulates the hypotheses for this study to develop a crisp set Quantitative Comparative Analysis (csQCA) based case analysis framework. Next, relevant case studies are identified to analyse and validate the framework using csQCA. The data for this study is collected from industry experts through semi-structured interviews. Finally, the results of the data analysis are presented and study concludes with a discussion of the study.

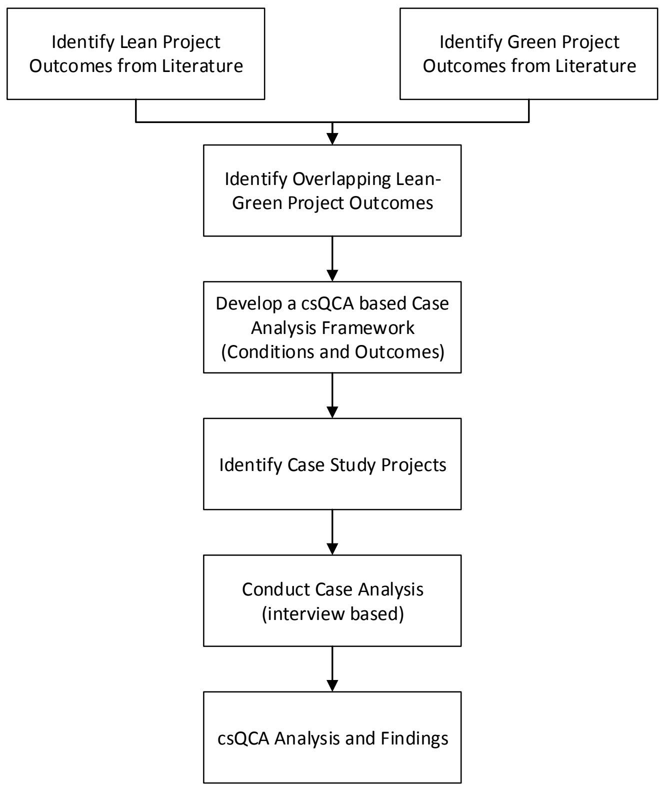

Figure 1: Flow Diagram showing Research Process

4.1 Hypotheses Formulation

According to a study by Sawhney (2014) it was found that the architectural firms, structural engineering consultants, mechanical, electrical and plumbing (MEP) consultants, construction management consultants and contractors are the top five organization types that are implementing BIM on their projects in India. Hence, for this study BIM capabilities related to these organization types were chosen and following hypotheses related to MEP System Modelling, Energy & Environment Analysis, Structural Analysis and Constructability Analysis were formulated.

One of the most commonly used BIM capability within Indian construction sector is MEP system modelling with 81% of the respondents reporting that usage of BIM leads to better MEP coordination (Sawhney, 2014). Autodesk (2006) defines MEP modelling as an effective solution for engineers to create MEP systems more accurately and easily with the help of available software. The report by Sullivan (2007) stated that MEP coordination using BIM and design-review technology can not only improve designs, system efficiency, job site scheduling and operational safety, but also provides the ability to identify, visualize and resolve conflicts amongst various building systems. Another research in China, indicated that MEP coordination helped to reduce the cost of the project and number of change orders (Yung et al., 2014). The study by Haiyan Xie et al. (2011) demonstrated how the use of BIM and MEP systems helped to improve employee productivity, reduce waste and pollution and thus diminished the overall impact of the built environment on human health and the natural environment Thus, this study hypothesizes that:

H1: Use of BIM-based MEP System modelling on construction projects contributes to lean and green project outcomes

Azhar et al. (2010) asserted cost savings as one of the realised benefits of BIM-based building performance analyses with a project in the US. Another study by Schlueter and Thesseling (2009) revealed that utilizing BIM for energy performance assessment allowed for a more integrated view of buildings during the early design stages which ultimately helps to achieve efficient designs for the buildings. A whitepaper released by Autodesk stated that with the use of BIM solutions, the implementation of sustainable design practices is easier as it enabled the architects and engineers to visualize, simulate, and analyse building performance earlier in the design process more accurately (Autodesk, 2010). Another study further stated that BIM solutions and integrated analysis tools helped to meet the sustainability and energy efficiency goals by assessing the building performance and evaluating design alternatives to reduce operational costs, conserve energy, reduce water consumption, and improve building air quality (Moakher and Pimplikar, 2012). Hence, this study hypothesizes that:

H2: BIM-based Energy and Environment Analysis at design stage of the projects lead to lean and green outcomes

Several reports document the benefits of using BIM for structural analysis and how it helps the structural engineers and other building industry professionals to create consistent, coordinated design models. Additionally it is also reported that the use of BIM for structural analysis can further help the project participants in visualizing, simulating, and analysing project performance and cost throughout the entire project lifecycle (Autodesk, 2012). Performing structural analysis helps project teams to detect coordination problems earlier in the project and thus, helping achieve more predictable outcomes. Hunt (2013) reported improvements in productivity, coordination and visualization as the important benefits of using BIM in structural engineering. Applying BIM in structural engineering leads to greater efficiency, improved quality, better design flexibility, more effective collaboration (Bernstein, 2006). In addition to this, BIM based structural analysis allows for a methodological structural documentation, constructible modelling, improved changed management, thus reducing cost, minimizing delays and rework (Autodesk, 2007; Tekla, n.d.). Thus, we hypothesize that:

H3: Performing BIM-based structural analysis on construction projects helps to achieve lean and green outcomes

Construction Industries Research and Information Association (CIRIA) defines constructability as the ability to use the collaborative design efforts during the construction phase and helping the contractors to determine and implement construction activities easily and smoothly (CIRIA, 1983). Further, Yang et al. (2013) has reported that BIM as a significant and effective tool for analysing constructability of designs before construction starts, avoiding the reworks and construction mistakes. Another study by Tauriainen et al. (2015) asserted that an understanding of constructability analysis lead to improved productivity and performance on the site. Smith (2014) stated that the main purpose of constructability review is to review the entire construction processes from start to end in the pre-construction or early design phase. And, further added that constructability review helps to identify and resolve various types of issues before the actual construction starts, thus helping to minimize errors, delays and cost overruns. Hence, we hypothesize that:

H4: BIM-based constructability analysis contributes to lean and green outcomes

5 Identification of lean and green benefits

An extensive literature review and continuous discussions with the industry experts helped in the identification of lean and green benefits for this study. These benefits were categorized under the three pillars of sustainability: Economic, Social and Environmental. Past research and documented case studies depicted that there are several lean benefits that are achieved as a result of applying green principles to construction projects. The study by Saggin et al. (2015) presented the benefits of implementing green principles by comparing the cost of initial investments in sustainability and the reduced cost due to reduction of materials' waste on a residential project. Similarly, a study by Shen et al. (2007) reported a framework of sustainability which helped improve the cooperation and coordination among all parties. Another study by Yeheyis et al. (2013) proposed a conceptual waste management framework for implementing sustainable and comprehensive strategy by maximizing the 3R (reduce, reuse and recycle) and minimizing the disposal of construction waste throughout the lifecycle of construction projects. The lean benefits as reported have been shown in Table 1.

Table 1: Lean benefits of applying green principles to construction projects

Economic	**Social**	**Environment**
Improved productivity	Health, safety and conducive working environment	Waste minimization and elimination
Client satisfaction	Building effective channels of communication	Design for whole-life costs
Minimizing defects	Participation in decision-making	Preservation of Resources
Lower project costs	Loyalty amongst stakeholders	
Shorter and more predictable completion time		
Delivering services that provide best value		
Increased performance		

Interchangeably, the studies also presented various green benefits of applying lean principles to construction projects. A study by Huovila and Koskela (1998) reported that the lean principle of flow and value help to meet the sustainability objectives of minimizing resource depletion, minimizing pollution and, matching business and environmental excellence. Peng and Pheng (2011) while identifying the contribution of the lean concepts to achieve sustainability in precast concrete factories, reported that by using appropriate lean principles, the precast concrete industry can move closer towards achieving sustainability. Another paper by AlSehaimi et al. (2013) evaluated the effectiveness of implementing the Last Planner System (LPS) in the Saudi construction industry and reported its green benefits as improved construction planning, enhanced site management and, better communication and coordination. The green benefits of applying lean principles to construction projects under the social, economic and environmental aspects have been mentioned in Table 2.

Table 2: Green benefits of lean implementation on construction projects

Economic	**Social**	**Environment**
Increased productivity	Improvement in health and safety	Reduction in waste
Optimization of resources	Increased organisational communication and integration	Improved process flow
Reduction in over ordering of materials	Client satisfaction	Reduction in material usage
Reduced costs and lead time	Increased levels of organizational commitment	
Less variability and improved predictability	Increased employee morale and commitment	
Construction project value enhancement	Information transparency	
Improvement in quality	Standardization of work practices	

Based on the above information and interactions with ten industry experts, the synergies between the two paradigms were used in determining ten combined lean and green outcomes on construction projects as shown in Table 3 below:

Table 3: Similarities between lean and green outcomes: Performance measures

P1- Reduced Rework	P4 - Cost Saving	P7 - Waste Reduction	P10 - Safe Workplace
P2 - Value Engineering	P5 - Faster Construction	P8 - Lead Time Reduction	
P3 - Enhanced Trust	P6 - Resource Optimization	P9 - Material Saving	

6 Research Method: Qualitative Comparative Analysis

QCA as proposed by Ragin (1987) is a configurational research approach which combines the strengths of qualitative (case-oriented) and quantitative (variable-oriented) research methods. Additionally, QCA analysis is capable of systematically examining the similarities and differences between a set of comparable cases to identify the structural conditions that lead to an outcome. Since the adoption of BIM in India is still in experimentation stage and BIM has not been explored to its full potential, csQCA is considered more appropriate than fsQCA. One of the major advantages of QCA is that it has the potential to identify equifinality or multiple conjunctural causation, i.e., in other words, QCA allows to assess complex causation between different combinations of causal conditions generating the same outcome. With its ability to identify combination of necessary and sufficient condition(s), QCA has now gained a wider acceptance across different research disciplines. Another reason for using QCA as a technique for this research is that it is systematic which means that QCA successfully uses a formal logic to compare cases, to explore causal diversity, and reduces the wealth of case information to achieve parsimony through minimization by using Boolean logic.

6.1 Introduction to csQCA

QCA constitutes of two configurational approaches each grounded in set theory. One approach uses crisp-sets (dichotomous variables) to analyse cases. The other approach uses fuzzy-sets.

Although the use of fuzzy-sets has been increasing over the last few years, but the use of crisp sets and the csQCA as outlined by Ragin (1987) is still used in a majority of empirical applications (Rihoux et al., 2013). For this research csQCA has been used and the various steps involved in performing csQCA as stated by Marx et al. (2013) are shown in Figure 2 below:

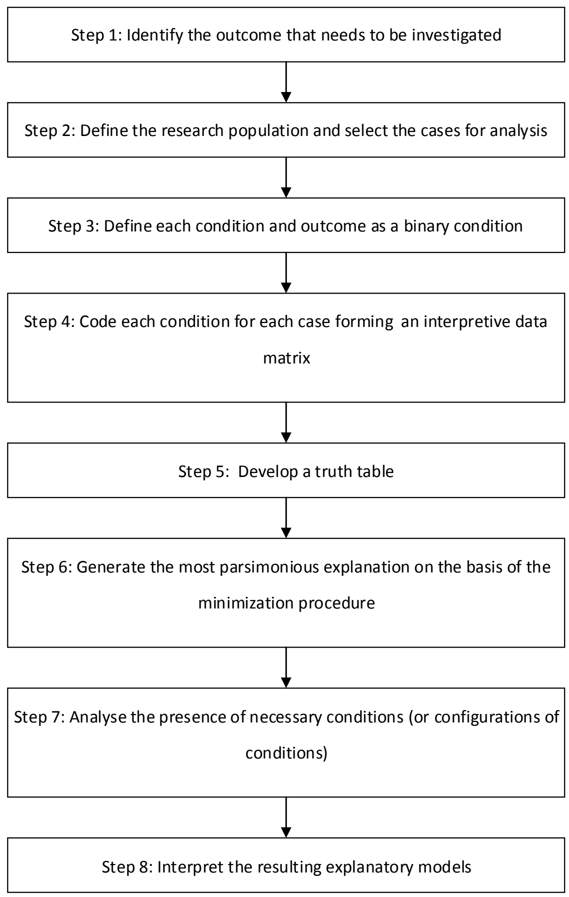

Figure 2: Steps for performing csQCA

6.2 Data Collection

The data collection was done with the help of semi-structured interviews as conducted with experts from four leading architectural organizations in India to obtain relevant case studies. The selected architectural organizations have been successfully contributing to the development of the Indian AEC sector for more than 15 years and working extensively on the building projects. It involved various interview sessions and discussions with the BIM experts in these organizations who were professionally qualified as architects, civil engineers and held above 10 years of experience in the industry. As a result, sixteen cases were examined where BIM capabilities were adopted on the construction projects. The total number of cases were found acceptable for conducting this study with a threshold of 5% (Marx et al., 2013). These cases were a mix of residential and commercial building projects mainly in their construction phase. In addition to this, the data was collected with an emphasis on lean and green outcomes obtained as a result of BIM usage on the projects. Each case was assessed with the presence and absence of conditions and benefits gained through their implementation.

6.3 Variables: Identification of Conditions

The outcome under study was a dichotomous variable: whether the organization achieved lean and green (L-G) outcome. QCA provides the freedom of defining the threshold between absence and presence for each condition and the outcome theoretically based on case knowledge (Sehring et al., 2013). For this research, a binary value of 1 was assigned to the specific case if five or more than five lean and green performance measures were present. Similarly, a binary value of 0 was assigned to the case for the presence of four or less than four lean and green performance measures. The antecedents or conditions comprised of the following variables:

- BIM-based MEP system modelling (MEP), assigned a value of 1 if the organization adopts MEP system modelling on the project, and 0 otherwise
- BIM-based Energy and Environment Analysis (E&EA), assigned a value of 1 if the organization uses energy and environment analysis on the project, and 0 otherwise
- BIM-based Constructability Analysis (CA), assigned a value of 1 if the organization uses constructability analysis on the project, and 0 otherwise

- BIM-based Structural Analysis (SA), assigned a value of 1 if the organization uses structural analysis on the project, and 0 otherwise

The different lean and green performance measures as found in each case have been documented in Table 4.

Table 4: Case-wise lean and green performance measures

CASES	**CONDITION**	**PERFORMANCE MEASURE**									
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**
COMMERCIAL 1	MEP	✓	✓	✓	✓			✓			
	E&EA		✓		✓						
	CA	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	SA			✓	✓	✓				✓	✓
COMMERCIAL 2	MEP	✓		✓	✓	✓	✓	✓	✓	✓	✓
	E&EA	✓	✓	✓	✓			✓		✓	✓
	CA										
	SA	✓	✓	✓	✓			✓		✓	✓
COMMERCIAL 3	MEP	✓		✓	✓	✓	✓	✓	✓	✓	✓
	E&EA	✓	✓	✓	✓			✓		✓	✓
	CA										
	SA	✓	✓	✓	✓			✓		✓	✓
COMMERCIAL 4	MEP	✓			✓			✓		✓	✓
	E&EA										
	CA	✓			✓						
	SA										
COMMERCIAL 5	MEP	✓			✓			✓		✓	✓
	E&EA										
	CA	✓			✓						
	SA										
RESIDENTIAL 1	MEP		✓		✓		✓	✓		✓	
	E&EA										
	CA	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	SA			✓	✓	✓				✓	✓
RESIDENTIAL 2	MEP	✓	✓	✓	✓						
	E&EA										
	CA	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	SA			✓			✓			✓	✓
COMMERCIAL 6	MEP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	E&EA	✓	✓		✓			✓			✓
	CA	✓	✓		✓		✓		✓		✓
	SA	✓	✓	✓	✓			✓		✓	
RESIDENTIAL 3	MEP	No performance measure reported									
	E&EA										
	CA										
	SA										
COMMERCIAL 7	MEP	No performance measure reported									
	E&EA										
	CA										
	SA										
RESIDENTIAL 4	MEP	No performance measure reported									
	E&EA										
	CA										
	SA										
RESIDENTIAL 5	MEP	✓	✓	✓				✓		✓	
	E&EA		✓								
	CA	✓									
	SA	✓		✓							
RESIDENTIAL 6	MEP	✓	✓	✓							
	E&EA										

	CA										
	SA										
COMMERCIAL 8	MEP	✓		✓				✓			
	E&EA		✓	✓							
	CA										
	SA										
RESIDENTIAL 7	MEP	✓		✓				✓			
	E&EA		✓	✓							
	CA										
	SA										
RESIDENTIAL 8	MEP	No performance measure reported									
	E&EA										
	CA										
	SA										

Note: MEP = MEP System modelling; E& EA= Energy and environmental analysis; CA = Constructability Analysis; SA= Structural Analysis; P1=Reduced Rework; P2 =Value Engineering; P3= Enhanced Trust; P4= Cost Saving; P5= Faster Construction; P6=Resource Optimization; P7= Waste Reduction; P8 = Lead Time Reduction; P9= Material Saving; P10= Safe Workplace

As a result, after computing the values for all the sixteen case studies, a crisp set interpretive data matrix table was obtained as shown in Table 5. Cases are grouped in an order intended to make the table ultimately easier to read/interpret.

Table 5: Interpretive Data Matrix Table of 'Lean-Green outcome' and BIM capabilities

S.No.	case ID	MEP	E&EA	CA	SA	L-G
1	Commercial 1	1	1	1	1	1
2	Commercial 2	1	1	0	1	1
3	Commercial 3	1	1	0	1	1
4	Commercial 4	1	0	1	0	1
5	Commercial 5	1	0	1	0	1
6	Residential 1	1	0	1	1	1
7	Residential 2	1	0	1	1	1
8	Commercial 6	1	1	1	1	1
9	Residential 3	1	0	0	0	0
10	Commercial 7	1	0	0	0	0
11	Residential 4	0	0	0	0	0
12	Residential 5	1	1	1	1	1
13	Residential 6	1	0	0	0	0
14	Commercial 8	1	1	0	0	1

15	Residential 7	1	1	0	0	1
16	Residential 8	1	0	0	0	0

7 Analysis

This section consisted of developing the truth table, analysis of the presence of necessary and sufficient conditions (or configurations of conditions); and interpretation of the resulting explanatory models.

7.1 Formulation of truth table of 'Lean-Green outcome' and BIM configurations

The truth table as shown in Table 6 represents a relationship between the cases, conditions and outcomes. Each row of the truth table represented one of the logically possible combinations of the conditions leading to the same outcome. Despite having sixteen case studies in the data set, the truth table reveals that limited diversity exists, that is, not all logically possible combinations between the conditions, MEP system modelling, energy & environment analysis, constructability analysis and structural analysis are empirically observed. This is true for the country like India where BIM is still in its experimentation stage and the full potential of BIM yet needs to be explored (Sawhney, 2014). 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, 2011) which is deemed as a useful tool for Small-N analysis.

Table 6: Truth Table of 'Lean-Green outcome' and BIM configurations

S. No.	MEP	E&EA	CA	SA	L-G	Cases
1	1	1	1	1	1	Commercial 1, Commercial 6, Residential 5
2	1	1	0	1	1	Commercial 2, Commercial 3

3	1	0	1	0	1	Commercial 4, Commercial 5
4	1	0	1	1	1	Residential 1, Residential 2
5	1	0	0	0	0	Residential 3, Commercial 7, Residential 6, Residential 8
6	0	0	0	0	0	Residential 4
7	1	1	0	0	1	Commercial 8, Residential 7

7.2 Identification of QCA Solution formula

The truth table is the most important aspect of QCA analysis which contains the most significant information regarding the relevant cases. The solution formula consists of the outcome and the causal conditions which are represented in letters that are linked with Boolean operators. The three basic Boolean operators are logical OR (+), logical AND (*), and logical NOT (where negation is customarily denoted in QCA by replacing an upper case letter with a lower case letter). After generating the truth table, further analysis not only helped to define the necessary conditions, but also generated the most parsimonious solution amongst all the possible combinations of the conditions leading to the outcome. The analysis revealed three sufficient antecedent combinations of BIM capabilities leading to lean and green outcomes as illustrated in Figure 3 :

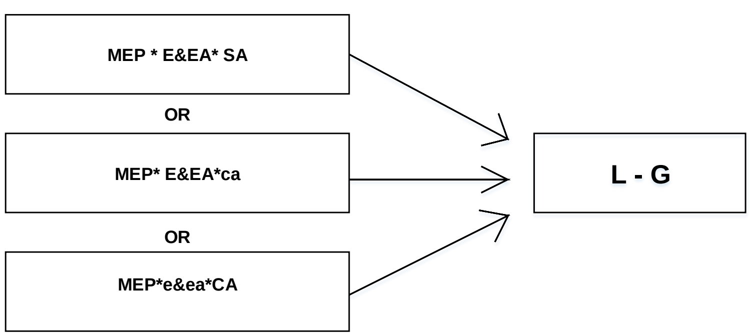

Figure 3: BIM capabilities solution formula

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 an understanding regarding constructability analysis (ca) OR use of MEP system modelling (MEP) AND absence of use of energy and environment analysis (e&ea) AND having a clear understanding of constructability analysis (CA).

7.3 Measures of Fit: Set-theoretic Consistency and Coverage

The two key parameters for assessing the fit of QCA results to the underlying data are consistency and coverage (Ragin, 2006). In a crisp-set relation , the measure of consistency with sufficiency is the proportion of cases with a given cause or combination of causes which also display the outcome (Grofman and Schneider, 2009; Ragin, 2006; Rihoux and Meur, 2009). Hence, for the combination MEP*E&EA*SA, five out of five cases displaying causal combination exhibit the outcome, therefore the proportion consistency is 5/5 = 1.00. Similarly, for the combination of MEP*E&EA*ca, four out of four cases displaying causal combination present the outcome, therefore the proportion consistency is 1.00. Again, for the third casual combination of MEP*e&ea*CA, four out of four cases display the outcome, hence, the proportion consistency is 1.00. The results in a more familiar cross-tab format are presented in Table 7 below.

Table 7: Sufficiency Conditions with L-G as the outcome variable

(a) Cross-Tab showing MEP*E&EA*SA as a sufficient condition for lean and green outcome	Not MEP*E&EA*SA	MEP*E&EA*SA	
No L-G	5	0	5
L-G	6	5	11
	11	5	N=16
(b) Cross-Tab showing MEP*E&EA*ca as a sufficient condition for lean and green outcome	Not MEP*E&EA*ca	MEP*E&EA*ca	

No L-G	5	0	5
L-G	7	4	11
	12	4	N=16
(c) Cross-Tab showing MEP*e&ea*CA as a sufficient condition for lean and green outcome	Not MEP*e&ea*CA	MEP*e&ea*CA	
No L-G	5	0	5
L-G	7	4	11
	12	4	N=16
(d) Cross-Tab showing MEP*E&EA*SA or MEP*E&EA*ca or MEP*e&ea*CA as a sufficient condition for lean and green outcome	Not MEP*E&EA*SA or MEP*E&EA*ca or MEP*e&ea*CA	MEP*E&EA*SA or MEP*E&EA*ca or MEP*e&ea*CA	
No L-G	5	0	5
L-G	0	11	11
	5	11	N=16

Note: MEP = MEP System modelling; E& EA= Energy and environmental analysis; CA = Constructability Analysis; SA = Structural Analysis

A direct measure of set-theoretic coverage for crisp sets is a clear indicator of the empirical importance of a causal combination (Ragin, 2006). The assessments of ‘raw’ coverage and ‘unique’ coverage suggests that combinations of conditions are highly consistent subsets of the outcome. It is further stated that it is reasonable to calculate coverage only after establishing that a set relation is consistent. Since, for this study, all the three causal combinations are found to be perfectly consistent, hence, the coverage calculations for all the three combinations have been discussed. Table 5 shows a total of eleven cases that display the presence of L-G outcome. The solution formula MEP * E&EA* SA + MEP* E&EA*ca + MEP*e&ea*CA covers all eleven of them. Hence, the solution coverage, namely, the overall coverage of all sufficient conjunctions combined, is 11/11 = 1.00. In this, MEP * E&EA* SA alone covers five out of eleven cases (rows 1 and 2) and its raw coverage, thus is 5/11 = 0.45. Similarly, MEP* E&EA*ca alone covers four out of eleven cases (rows 2 and 7) and its raw coverage, thus is 4/11 = 0.36. In addition to this, the causal combination MEP*e&ea*CA alone covers four out of eleven cases (rows 3 & 4) and its raw coverage, thus is 4/11 = 0.36.

For calculating the unique coverage of each of the combinations, similar template as provided by regression analysis is followed which involves calculation by subtraction. Thus, the unique coverage of MEP * E&EA* SA, that is, all the cases covered by MEP * E&EA* SA alone, is calculated by subtracting the sum of raw coverage of MEP* E&EA*ca and MEP*e&ea*CA (0.36 +0.36) from the solution coverage (1.00). Hence, unique coverage of MEP * E&EA* SA is (1 – 0.72) = 0.28. Similarly, the unique coverage of other causal combinations of conditions are calculated resulting in unique coverage of MEP* E&EA*ca = 0.19 and for MEP*e&ea*CA = 0.19 respectively. The collective results of this study have been summarised in the Table 8 below:

Table 8: Crisp set QCA analysis results

Causal configuration	Raw coverage	Unique coverage	Consistency
MEP * E&EA* SA	0.45	0.28	1.00
MEP* E&EA*ca	0.36	0.19	1.00
MEP*e&ea*CA	0.36	0.19	1.00
Solution coverage: 1.00			
Solution consistency: 1.00			

The solution set of antecedent combinations presents coverage and consistency as 1.00. Consequently, this solution explains 100% possibility of obtaining lean and green results on implementation of BIM capabilities.

8 Research Findings

It is found that all the three causal combinations depict perfect consistency (in general, consistency scores should be as close to 1.0 (perfect consistency) as possible (Ragin, 2006)) which further asserts that an integral connection exists between the causal combinations of BIM capabilities and the outcome: lean and green. These results are in congruence with the existing studies showing connections between BIM and lean; BIM and green (Ahankoob et al., 2012; Gerber et al., 2010; Rahman et al., 2013; Wong and Fan, 2013).

With respect to the raw coverage, the causal combination of MEP*E&EA*SA which shows the raw coverage of 0.45 explains that there is a 45% possibility of the project to attain lean and green outcomes by using BIM on projects. In addition, this causal combination alone depicts a unique coverage of 0.28 which explains that there is a 28% possibility of attaining lean and green outcomes when a combination of MEP System modelling, energy and environmental analysis and structural analysis are used on any construction project. Similarly, both the remaining causal combinations i.e., MEP*e&ea*CA and MEP*E&EA*ca show the raw coverage of 0.36 which explains that there is 36% possibility of the project to gain lean and green outcomes with implementation and combination of these BIM capabilities on construction projects. Along with this, the analysis further revealed that both these combinations show a unique coverage of 0.19 which means that if either of these combinations of BIM capabilities are used on the construction projects, there is 19% possibility of attaining lean and green outcomes.

With the above analysis, it was concluded that a combined use of MEP * E&EA* SA OR MEP* E&EA*ca OR MEP*e&ea*CA on construction projects yields lean and green outcomes. This was also found in congruence with the existing research reporting benefits of BIM (Czmoch and

Pękala, 2014; Johansson et al., 2014; Khanzode et al., 2008; Manning and Messner, 2008; Mcintosh et al., 2015).

It was also reported that MEP system modelling is a necessary condition, as it is a part of all observed solutions leading to the outcome. These results are consistent with the previous findings where implementation of MEP system modelling on construction projects has resulted in lean and green benefits of cost, time and material savings; reduced rework and value engineering (Khanzode et al., 2008; Mcintosh et al., 2015). Hence, the hypothesis stating that use of BIM-based MEP system modelling on construction projects contributes to lean and green project outcomes (H1) is accepted. Similarly, the results are in congruence with the previous findings where use of energy and environmental analysis (H2) at design stage of the projects helps to achieve efficient design solutions (Azhar et al., 2010). In addition to this, the existing literature also depicts that successful implementation of BIM-based structural analysis on construction projects (H3) has resulted in improved productivity, greater efficiency, better design flexibility and improved coordination (Bernstein, 2006; Hunt, 2013). Further, the findings of this study also confirm that BIM-based constructability analysis contributes to lean and green outcomes (H4) through reported reduced rework, minimized errors, improved productivity and performance (Smith, 2014; Tauriainen et al., 2015; Yang et al., 2013).

9 Conclusion

The question that "can BIM promote lean and green project outcomes?" has been answered in this research. This study confirms that use of BIM helps in achieving lean and green outcomes on construction projects. Although the findings result from analysing a sample of small size from architectural firms only, these findings are useful for the construction sector which is trying to overcome various environmental, poor project delivery and low productivity related challenges.

The study also suggests that the AEC firms should consider adopting BIM on projects for obtaining desired results.

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