Journal of Cleaner Production 174 (2018) 788–806

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Interactions of Building Information Modeling, Lean and Sustainability on the Architectural, Engineering and Construction industry: A systematic review

Pedro Saieg [a, b, *], Elisa Dominguez Sotelino [a], Daniel Nascimento [a, b], Rodrigo Goyannes Gusmão Caiado [c]

[a] Department of Civil Engineering, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil
[b] Tecgraf Institute of Technical-Scientific Software Development of PUC-Rio, Rio de Janeiro, Brazil
[c] Department of Post-Graduation in Sustainable Management Systems, Federal Fluminense University, Niteroi, Brazil

A R T I C L E I N F O

Article history:
Received 17 October 2016
Received in revised form
1 November 2017
Accepted 6 November 2017
Available online 7 November 2017

Keywords:
Building information modeling
Lean construction
Green construction
Synergies
Sustainable development

A B S T R A C T

Many studies have been conducted on the fields of Building Information Modeling, Lean construction and Sustainability not only individually but also pairwise. Despite that, there are currently no researches that integrate these concepts collectively. The aim of this paper is to combine these technologies, methods and concepts to fill this gap targeting the Architecture, Engineering and Construction industry by proposing a way in which concepts could coexist and complement each other. To that end, a systematic literature review was conducted to understand how synergies between these fields have recently been explored by researchers. Results indicate synergies mainly on the construction stages but also on the project process specially during conceptual design decision making. The presented integration provides significant opportunities to reduce economic and environmental impacts and in the future may be responsible for a great leap in efficiency to one of the least efficient industries worldwide.

1. Introduction

Over time, sustainable concerns have increasingly gained importance in the Architectural, Engineering and Construction (AEC) industry. In the last decade, there has been a growing pressure in terms of not only improving quality, productivity, efficiency and effectiveness, but also sustainable development. Among the challenges for the sustainability of the construction sector, there are: excessive material and process waste, over reliance on resources, high energy usage, carbon footprint and carbon emissions, poor project delivery and low productivity (Ortiz et al., 2009; Khoshanava et al., 2013; Dadhich et al., 2015; Ahuja et al., 2017). Besides that, as Alwan et al. (2017) observes, there is a need to improve the strategic vision with regard to sustainability, resistance to the implementation of new, more efficient technologies and inefficient logistics and communication methods.

In the current context, environmental, social and economic concerns and pressures have contributed to construction industry taking a proactive role in adopting new Building Information Modeling (BIM) based technologies and lean based methods, as well as developing sustainable services and manufacturing processes. The studies carried out by Sacks et al. (2010) and Arayici et al. (2011) explain how BIM contributes directly to lean goals on construction projects. Simultaneously, academics and practitioners have extensively cited the benefits of the alignment between lean thinking and sustainability/green (Ogunbiyi et al., 2013; Garza-Reyes, 2015; Fercoq et al., 2016).

Many researchers, such as Jrade and Jalaei (2013); Alwan et al. (2015) and Jalaei and Jrade (2015) have also asserted the relationship between BIM and green by confirming the sustainable benefits achieved through BIM implementation in the AEC industry. However, despite these studies, the academic literature and research lines exploring the impacts of BIM-lean practices on sustainability performance, potential synergies of BIM, lean and green concepts and their integration as a single and unique approach still remain in early stages. Also, there is a lack of studies about BIM and lean that

* Corresponding author. Department of Civil Engineering, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil.

E-mail addresses: pedrosf@tecgraf.puc-rio.br (P. Saieg), edsotelino@gmail.com (E.D. Sotelino), danielmn@tecgraf.puc-rio.br (D. Nascimento), rodrigoggcaiado@gmail.com (R.G.G. Caiado).

https://doi.org/10.1016/j.jclepro.2017.11.030
0959-6526/

takes into account the social, economic and environmental dimensions of sustainability. Therefore, the combination and the collective understanding of BIM, lean and green is necessary to address the current problems of the construction industry (Ahuja et al., 2017).

1.1. Building Information Modeling

During the last two decades, BIM has been exponentially growing as an intelligent 3D model-based process to equip professionals with information technology tools to more efficiently plan, design, construct and manage facilities, also improving the quality of produced documentation, constructability as well as enabling more proactive decision making. Its foundation is the structured, centralized, defined, easy access and exchangeable information (Hamdi and Leite, 2012; Sacks et al., 2009).

Changes in the project are inevitable due to its iterative and exploratory nature, in which content and structure are not static, but subject to continuous changes, especially in accelerated projects, even after construction has started. Thus, successful design changes management is fundamental for efficient project delivery and for this reason BIM is expected to play a key role in identifying the impacts of changes in projects and in integrating the processes of conception, construction and operation (Behzad et al., 2015).

The potential of BIM methodology in supporting the transformation of project and construction processes has been evident in the industry, considering that it supports improving design quality by eliminating conflicts and reducing rework, and is most frequently perceived as a tool to visualize and coordinate AEC (Architecture, Engineering and Construction), avoiding errors and omissions, improving productivity, supporting scheduling, safety, costs and quality management in construction projects (Chen and Luo, 2014). By also supporting more complex components and calculation due to its parametric and automated nature, BIM can significantly ease sustainable assessment processes, thus enabling a more consistent decision-making process at early stages.

1.2. Lean thinking

Lean Thinking proposes a way of “doing more with less” - less effort, less equipment, less personnel and less space - and targets reaching what indeed adds value to clients in the leanest way, eliminating wastes through more efficient processes that optimize the main competences of the value chain in production (Comm and Mathaisel, 2005). To Salehi (2015), lean thinking works as a transformational system that operationalizes organizational learning, promoting innovation, which in turn enables companies to manage limited resources.

Based on the lean thinking approach and reports stating the industry of construction as one of the least efficient, a number of methods and tools have been studied and developed to transform the construction process into a more easily manageable, safer, completed sooner, with better quality and at the same time costing less than traditional ones. On the other hand, such methods may require adaptations to face current environmental challenges (Kurdve et al., 2015) even though lean initiatives require less space for operation and storage, which in combination with a production less prone to defects, decreases use of energy and resources, thus promoting substantial environmental advantages (Wong and Wong, 2014).

According to Sacks et al. (2010), two important segments are accomplishing fundamental changes in the AEC industry. The first is a conceptual approach for construction project and management - Lean Construction - and the second is a transforming information technology - BIM. Although they are conceptually independent and most professionals and companies are still experiencing the learning curve, they appear to have synergies that if rooted in conceptual understanding of the theory of production and correctly understood can be explored to improve the construction process.

1.3. Sustainability

The concept of sustainability was proposed in 1987 by the World Commission on Environment and Development as an answer to the exponentially increasing effects of human interventions in nature and the severity of economic, social and environmental problems is closing the window of opportunity of “not doing further harm”. The construction sector is the biggest responsible for CO_2, the dominant gas emitted by human activity, thus usually considered when evaluating environmental impacts (Li et al., 2012; Oti and Tizani, 2015).

To Piercy and Rich (2015) it is clear that the improvement of using lean concepts, like using less resources, improving quality and reducing rework, waste, energy/water consumption and pollution costs provided a basis for improving sustainability and on the other side, sustainable practices support a variety of lean transformation objectives.

The escalation of energy costs and the necessity of increasing energy efficiency has been calling attention of society regarding the need to reduce energy consumption and incited efforts to integrate green and sustainable construction initiatives in the conventional project, construction and operation processes. BIM based technologies are considered potentially useful tools to aid stakeholders in capturing consistent model and design information to make best use of this available data to evaluate the level of sustainability and to develop a more sustainable design, aiming at increasing energy efficiency and reducing its consumption during the whole life cycle of a building (Wong and Kuan, 2014).

Thus, BIM is a novel technological approach to the design and manufacture of construction components (Alwan et al., 2017), with the potential to produce high-performance facility design (Azhar et al., 2011), which offers resource savings during design, planning and construction of new buildings (Bryde et al., 2013), while lean is a production management-based approach that works to minimize waste and achieve maximum value (Ahuja et al., 2017). This philosophy of management is more oriented to delivering products or services with resource efficiency, focusing on clients and employees, while sustainability practices or green is concerned with the capability of meeting the needs of all stakeholders in the present and future (Len and Calvo-Amodio, 2017), with the reduction of environmental impacts and the efficient use of resources.

1.4. Scope of research

Following the rise of these three fields, many researches have been conducted to study more deeply each of these concepts and in some cases their relation pairwise. But even though there is an increasing volume of research in these fields, there is still little or no research that relates the three concepts or how to apply this synergy in the industry. Considering the possible synergies that the combinations of these principles present pairwise, the aim of this review is firstly to cover what has been studied regarding these synergies, highlighting well explored topics and encountered limitations, and secondly identify how these three concepts can relate cohesively to improve the AEC industry, proposing future research objectives. Hence, this study proposes a systematic literature review in order to find and analyze the interactions of BIM, lean and sustainability on the Architectural, Engineering and Construction industry. The interactions between the principles of lean construction and the functionalities of BIM were based and inspired by the ideas of Sacks et al. (2010).

The evolution of the construction industry has recently had as protagonists the concepts of BIM, lean construction and sustainable designs. To understand current research attempts of relating these fields pairwise and to identify barriers and synergies of implementing the three concepts together, the following questions were considered:

- Research question 1: How do lean-BIM, green-BIM and lean-green interact in the AEC domain?
- Research question 2: How can BIM functionalities and lean principles contribute to sustainable development challenges of construction projects?

Furthermore, specifically, this research's contribution is three-fold. First, we enhance the knowledge of the interrelationships of BIM, lean and sustainability by analyzing their interactions in the AEC industry, considering societal, economic, and operational standpoints. Second, we summarize synergies, benefits (B), challenges (C) and problems(P) of this integration. Third, and based on the results from the synergies between BIM, lean and sustainability we propose a series of interactions and a matrix that can be viewed as prerequisites for the development of a BIM-lean-green integration in the industry.

The remainder of this article is structured as follows: section 2 presents the research methodology conducted, explicating which keywords were used, the procedure taken to find articles and the inclusion/exclusion criteria used to form the basis of articles reviewed. Section 3 summarizes the findings found, both quantitative and qualitative and section 4 presents how pairwise interaction has been explored by recent studies and the author's view on how BIM functionalities, lean principles and sustainability can interact cohesively for better construction projects. Finally, conclusions are presented followed by future research objectives on section 5 based on encountered results.

2. Research methodology

An extensive number of researches is conducted every year, many times with conflicting results. Targeting at identifying gaps on the subject of research and to direct further research on the same subject, the concept of systematic literature reviews was developed.

This review can be classified as a systematic review, because it adheres to the following principles observed by Briner and Denyer (2012): (1) be conducted by a systematic system or method; (2) present a transparent and explicit method; (3) be replicable and updatable; and (4) summarize and synthesize the evidence regarding the issue of review. Moreover, it started by the definition of an evaluation protocol, specifying the research question to be addressed and the methods used to realize such evaluation.

Furthermore, in this review, just as Caiado et al. (2017) and Viegas et al. (2016) highlighted, many articles were read, focusing on the scope of the research and limiting the sample to selecting, evaluating, and interpreting only relevant and adherent works for the particular subject. By documenting the strategy of research, allows the reader to assess its rigor as well as its completitude and the repeatability of the process. The selection of primary studies by explicit inclusion and exclusion criteria are fundamental features required not only to make the process transparent but also to provide the reader the knowledge of what was not covered by the review.

An effective review creates a firm foundation for advancing knowledge. It facilitates theory development, closes areas where a plethora of research exists, and uncovers areas where research is needed (Webster and Watson, 2002). As SLRs provide highly procedural and analytic objectivity and replicability, they have increasingly been used in literature management (Hallinger, 2013). Among its main advantages, the following can be highlighted:

- Well defined methodology makes it less likely that literature results are biased;
- If studies provide consistent results, systematic reviews highlights evidences that the phenomenon is robust and transferable;
- In the case of quantitative studies, it is possible to combine data using meta-analysis techniques, increasing the likelihood of detecting real effects that smaller studies are not capable of determining.

Its main disadvantage is the fact that it requires much more effort when compared to conventional literature reviews.

Following considerations of Denyer and Tranfield (2009); de Medeiros et al. (2014); Garza-Reyes (2015), this review consists of the following five consecutive stages: (1) question formulation, (2) locating studies, (3) study selection and evaluation, (4) analysis and synthesis and (5) reporting and using of results. According to Saunders et al. (2012), for reasons of transparency, it is essential to explain thoroughly how the review process was conducted, particularly regarding the section of the literature and the choices made in relation to the use of specific search terms and databases. The framework depicted in Fig. 1 helps to illustrate and summarize the stages conducted in the undertaken review, the methods and tools used to support each stage as well as the section of the text in which each stage is addressed.

Even though the review conduction seems sequential, it is important to recognize that many of these stages involve interactions. For example, the selection of primary studies is governed by the criteria of inclusion and exclusion, which are specified in the beginning of the process but can then be refined when better quality filters are determined.

2.1. Locating studies

The search strings used to find the most relevant studies were based on a words tree, concept of Dantas Gabriele et al. (2012), constructed through considering relevant terms found in the literature of the subjects of interest. According to Siddaway (2014), search strings operationalize research questions and help finding the maximum amount of articles potentially relevant for the research. Alternative terms must also be taken into consideration since it is common that a range of words are used to describe the same area. Thus, two levels of terms were defined as shown in Fig. 2.

The initial research string was defined using boolean operators "AND" and "OR" as specified in Table 1 but almost no results were found, making it even more clear that there is a research gap that needs to be filled. Thus, the research string was subdivided in three, combining pairwise the main keywords as specified in the second column of Table 1. This review did not consider searching for each concept individually, since there has been already extensive work in each of the areas separately.

Study location was conducted considering search strings in various databases to find the most relevant articles. Scopus (scopus.com), Elsevier (sicencedirect.com), Emerald (emeraldinsight.com) and Engineering Village (engineeringvillage.com) were chosen. Google Scholar (scholar.google.com) was used for validation. Even though the use of multiple databases generated a great amount of duplicates, their use ensured that almost every study that should be

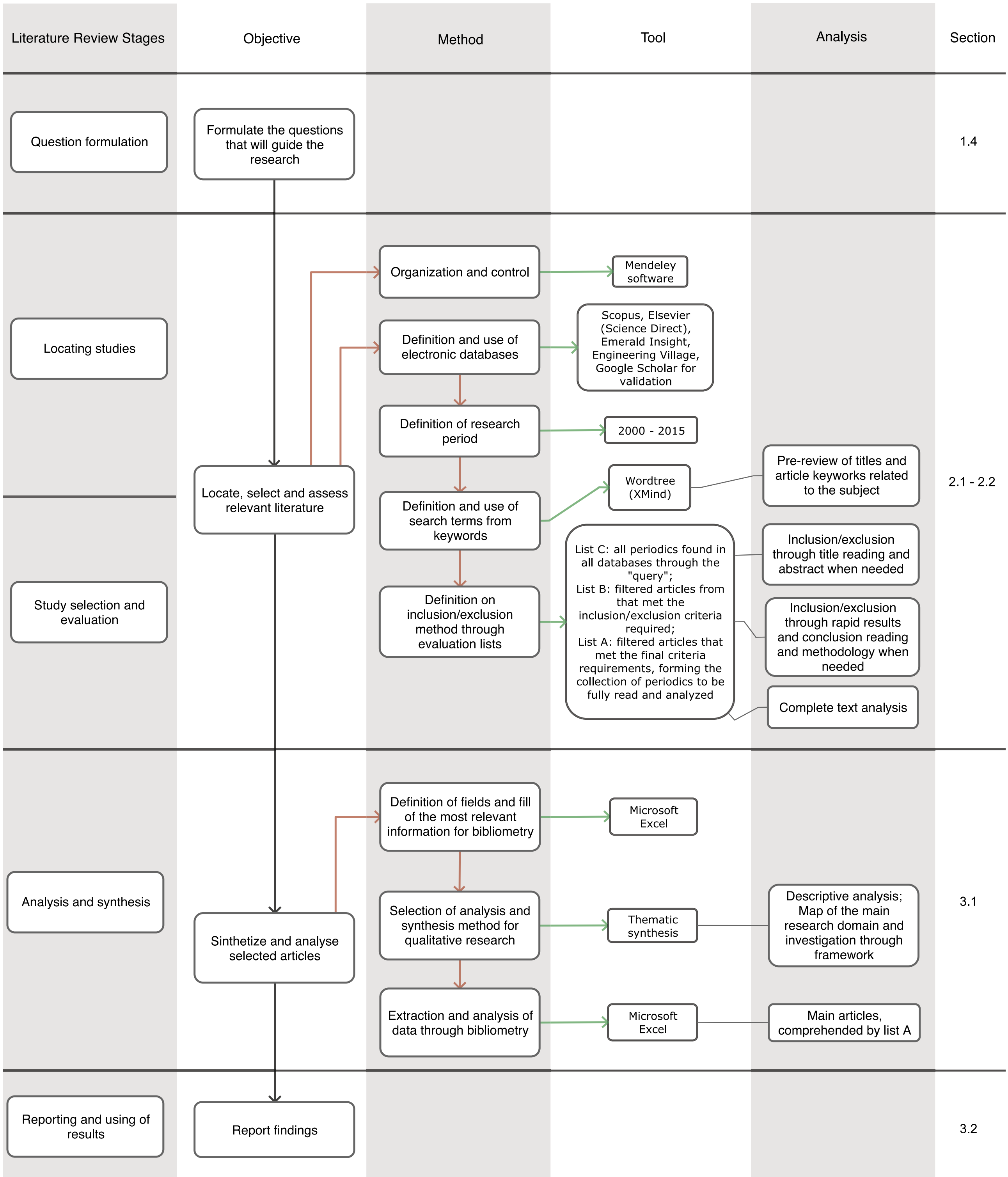

Fig. 1. Framework of the research methodology undertaken.

considered was found, since there is no single database that contemplates all articles of a given subject. To centralize, organize and control the obtained results, reference manager Mendeley was used allowing annotations, search within documents and easy removal of duplicates.

2.2. Study selection and evaluation

According to Saunders et al. (2012), only peer-reviewed articles and conference proceedings should be considered since these are the most useful and reliable sources for literature reviews. As for the period of research, 2000 to 2016 was chosen because since the

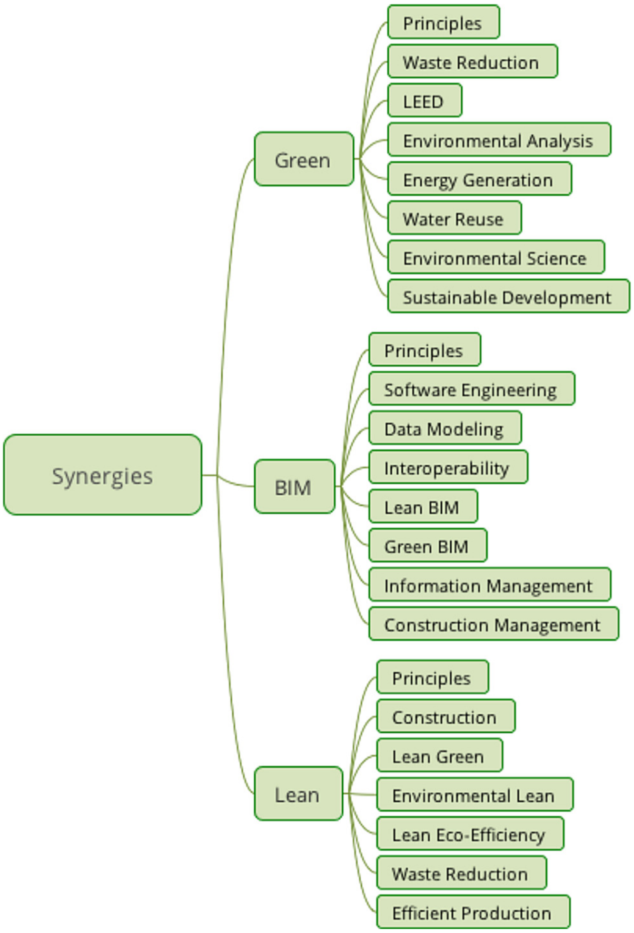

Fig. 2. Search terms wordtree.

Table 1
Strings of search terms.

Initial string	Subdivided strings
Sustain* AND (Green principles OR Waste reduction OR …) AND BIM AND (Principles OR Software engineering OR …) AND Lean AND (Principles OR Construction OR …)	Sustain* AND (Green principles OR Waste reduction OR …) AND BIM AND (Principles OR Software engineering OR …) BIM AND (Principles OR Software engineering OR …) AND Lean AND (Principles OR Construction OR …) Sustain* AND (Green principles OR Waste reduction OR …) AND Lean AND (Principles OR Construction OR …)

beginning of the millennium sustainability has become a major concern of society and has since than received bigger investments. Another reason is that it is also clear that the growth of publication in the matter has grown exponentially during this period. A few articles could not be considered because their full texts were not available. Reim et al. (2015) affirms that the resulting group of articles found must be refined through three steps:

- For Siddaway (2014), a first step includes reading titles and abstracts of each study found and evaluating wether it initially meets inclusion criteria or not;
- The second step comprehends reading the text focusing on sections of methodology and conclusion and checking if the article meets the required criteria (Siddaway, 2014);
- For the remaining studies, extract all information through carefully reading the full text.

Criteria of inclusion and exclusion must be implemented objectively, explicitly and consistently, in a way that the decision for inclusion or exclusion is clear and if another researcher would go through the same process, he or she would make the same decision. This approach aims at minimizing possible bias from the author (Siddaway, 2014). Table 2 summarized the criteria used in this research. The initial selection result returned 811 texts on list C after duplicate removal, further filtered to 143 on list B, with a final selection of studies including 32 articles on list A which were fully read and followed to have their information of interest extracted providing a descriptive and a thematic analysis.

3. Findings

Results are structured as follows: first, a brief consideration of quantitative results and a thematic synthesis to help readers find the information they seek faster is presented on section 3.1. Then, a descriptive analysis of main objectives of each authors's researches considered on this study followed by a table that presents the main findings for “BIM and Lean”, “BIM and Green” and “Lean and Green” are described on sections 3.2.1, 3.2.2 and 3.2.3 respectively.

3.1. Descriptive analysis

Fig. 3a shows that even though publications are slightly scattered, there is a growing research tendency specially for BIM and sustainability topics, with lean somewhat stagnated. It also displays that despite the fact that this review considered publications since the year of 2000, it was only from about 2006 that studies combining these topics started emerging.

Fig. 3b demonstrates the large disparity in publications from the United States and United Kingdom when compared to others countries. Considering countries that presented at least one article and the fact that only papers that presented pairwise combination of topics were analyzed, Brazil, Chile and Sweden had no BIM related articles, while Canada, China and France had no Lean related articles and Israel presented no Green related papers. It is interesting to notice in Fig. 3c that even though the United States presents a bigger volume of published articles, it is the United Kingdom that has been recently growing significantly, which may be directly related to the BIM Task Group (2013) initiative, that demands BIM use for any government related project and also has the objective of reducing by 50% greenhouse gas emissions by 2025.

Table 3 presents the list of articles reviewed and their associated numbers to facilitate understanding of the thematic synthesis depicted on Fig. 4, that subdivides articles over their method, approach and which of the 5Ds of sustainability (Economic, Environmental, Governance, Social and Technical), defined by Singh et al. (2007), they somehow benefit in the author's perception.

Table 2
Inclusion and exclusion criteria.

Inclusion	Exclusion
Combines at least two of the concepts	Studies only one of the concepts
Applied on the AEC industry or studies concepts generally	Applied in other areas Mentions environment but not as an aspect of sustainability (e.g. work environment) Mentions sustainable but not as proposed by this research (e.g. sustainable economy)

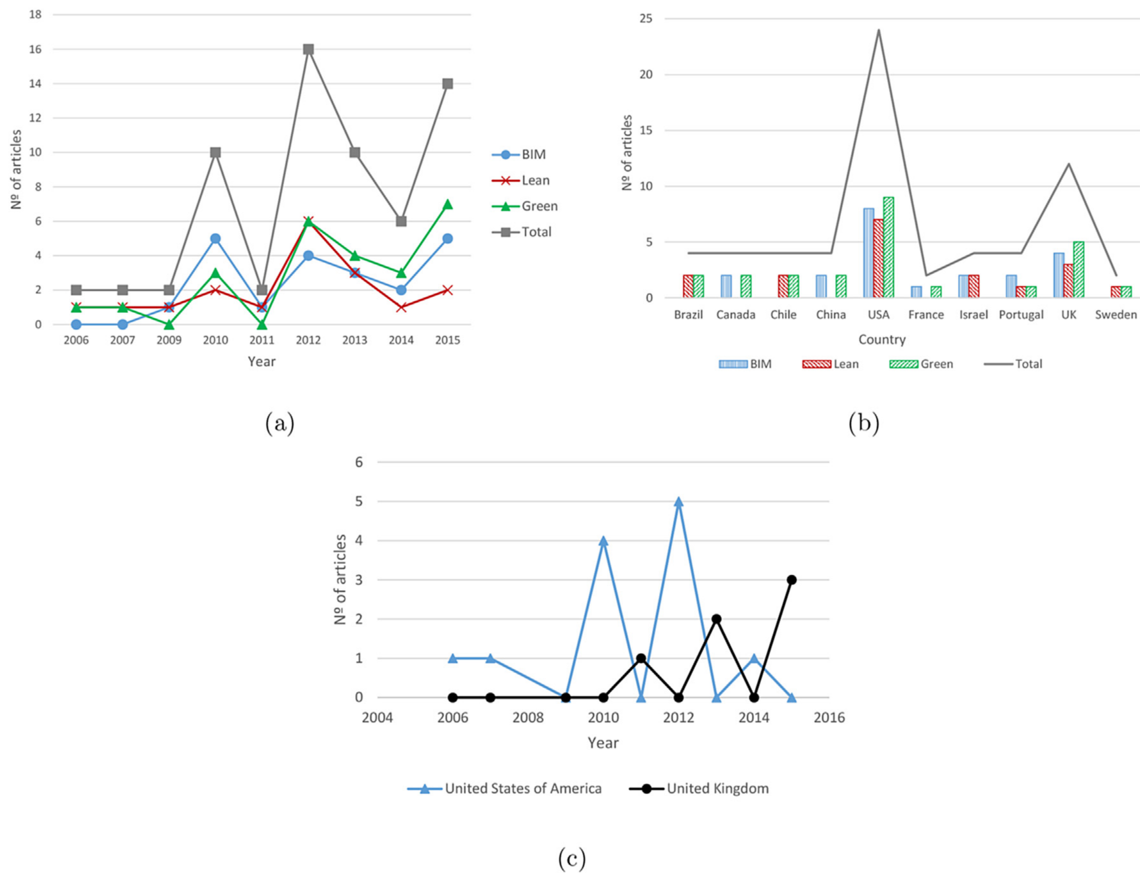

Fig. 3. (a) articles per year for BIM, Green and Lean, (b) articles per country for BIM, Green and Lean, (c) total articles per year on the UK and USA.

3.2. Content analysis

3.2.1. BIM and Lean

Hamdi and Leite (2012) identified relationship aspects of BIM and lean mainly focusing on the construction phase and in the perspective of a general contractor that is already used to BIM but has only recently started considering lean practices. The aspects are identified based on a case study of a hospital construction and considering Sacks et al. (2010) previously developed matrix of relationship. The greatest contribution is the identification of BIM maturity levels that are highlighted by the implementation of lean practices.

Dave et al. (2011) proposed a prototype software (VisiLean) that provides the construction team a BIM integrated lean management system that clarifies task status visualization through visual indicators embedded in the 3D model and available to all workers, allows the implementation of the Last Planner System (LPS) and provides better quality discussions based on 3D visualization where it would be difficult based on traditional drawings. Even though the system was not yet applied on a real case project, it has been shown to industry professionals with positive feedback.

Clemente and Cachadinha (2013) aimed at analyzing through a Value Stream Map (VSM) how activities are being conducted on a Mechanical, Electrical and Plumbing (MEP) renovation project, identifying tasks duration and value adding activities, and defining procedures to be taken based on lean principles and solutions with collaborative participation on two daily meetings to define which activities were finished and the next day's schedule based on the LPS with the aid of a BIM model. The case study is used to associate lean principles to each BIM functionality implemented. BIM proves to be a great asset to facilitate lean construction practices.

Oskouie et al. (2012) sought to expand Sacks et al. (2010) relationship matrix exploring and explaining new interactions between these by proposing other functionalities and principles based on industry cases and academic projects especially during operation phase, also identifying wether these interactions have already been found in the literature. Most researched lean principles include “Reduce Variability” and “Reduce Cycle Times”, demonstrating a focus on efforts of prevention and scheduling. On BIM's side, “Reuse of Model Data for Predictive Analyses”, “Visualization of Form”, “Facilitating Real-Time Construction Tracking and Reporting” and “Facilitating Retrieval of Real-Time Integrated Building, Maintenance and Management Data” are the most studied, evidencing an interest in technologies of “Real-Time Data Acquisition” and Analysis” that integrated with visualization provided by BIM can significantly facilitate the decision making process.

Sacks et al. (2009) presented two prototype software interfaces developed to facilitate process flows implemented on the context of BIM systems. Both systems use BIM model based visualization to implement lean construction methods and facilitate understanding of construction processes on a transparent way.

Sacks et al. (2010) rigorously examined interactions between lean principles and BIM functionalities through a relationship matrix to determine wether synergies exist or not and to serve as a conceptual framework for future research to explore the applications of each cell. They also describe efforts that aimed at exploring the existing synergy between the areas, like a study by Rischmoller et al. (2006) which integrated lean principles with Computer Aided Visualization Tools (CAVT) emphasizing value generation during the design phase.

Table 3
Articles included in the literature review.

No	Authors	Article
1	Alwan et al. (2015)	Rapid LEED evaluation performed with BIM based sustainability analysis on a virtual construction project
2	Garza-Reyes (2015)	Lean and green-a systematic review of the state of the art literature
3	Amado and Poggi (2014)	Solar Urban Planning: A Parametric Approach
4	Azhar et al. (2010)	A case study of building performance analyses using building information modeling
5	Azhar et al. (2011)	Building information modeling for sustainable design and LEED rating analysis
6	Bae and Kim (2007)	Sustainable value on construction project and application of lean construction methods
7	Biswas and Krishnamurti (2012)	Data sharing for sustainable building assessment
8	Carneiro et al. (2012)	LEAN and green: A relationship matrix
9	Clemente and Cachadinha (2013)	BIM-lean synergies in the management on MEP works in public facilities of intensive use - A case study
10	Dave et al. (2011)	VisiLean: Designing a production management system with lean and BIM
11	Dues et al. (2013)	Green as the new Lean: How to use Lean practices as a catalyst to greening your supply chain
12	Gerber et al. (2010)	Building information modeling and lean construction: Technology, methodology and advances from practice
13	Hamdi and Leite (2012)	BIM and Lean interactions from the BIM capability maturity model perspective: A case study
14	Inyim et al. (2014)	Integration of building information modeling and economic and environmental impact analysis to support sustainable building design
15	Jalaei and Jrade (2015)	Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings
16	Jrade and Jalaei (2013)	Integrating building information modeling with sustainability to design building projects at the conceptual stage
17	Koranda et al. (2012)	An investigation of the applicability of sustainability and lean concepts to small construction projects
18	Kurdve et al. (2015)	Waste flow mapping to improve sustainability of waste management: A case study approach
19	Lapinski et al. (2006)	Lean processes for sustainable project delivery
20	Li et al. (2012)	Research on the computational model for carbon emissions in building construction stage based on BIM
21	Liu et al. (2015)	Building information modeling based building design optimization for sustainability
22	Motawa and Carter (2013)	Sustainable BIM-based Evaluation of Buildings
23	Nguyen et al. (2010)	Evaluating sustainability of architectural designs using building information modeling
24	Novak (2012)	Value paradigm: Revealing synergy between lean and sustainability
25	Oskouie et al. (2012)	Extending the interaction of building information modeling and lean construction
26	Oti and Tizani (2015)	BIM extension for the sustainability appraisal of conceptual steel design
27	Rosenbaum et al. (2014)	Green-lean approach for assessing environmental and production waste in construction
28	Rosenbaum et al. (2012)	Improving environmental and production performance in construction projects using value-stream mapping: Case study
29	Sacks et al. (2009)	Visualization of work flow to support lean construction
30	Sacks et al. (2010)	Interaction of lean and building information modeling in construction
31	Salgueiro and Ferries (2015)	An "environmental BIM" approach for the architectural schematic design stage
32	Valente et al. (2013)	Lean and green: How both philosophies can interact on strategic, tactical and operational levels of a company

Gerber et al. (2010) aimed to expose through case studies applications of BIM-lean interactions previously described by Sacks et al. (2010) in order to validate how BIM can ease lean construction measures from design to construction and operation. They explore use of BIM and the synchronizing with scheduling software solutions and experts to reduce waste caused by poor coordination and to maximize value for the entire project constituency by ensuring Look-Ahead collaboration.

Table 4 presents the main conclusions found by the authors after conducting their researches, also referencing where each finding can be encountered in the literature.

3.2.2. BIM and green

Alwan et al. (2015) verified the viability of using information flow processes of a BIM model to speed up environmental assessment in terms of LEED certification through a case study of a competition in which participant teams should rapidly evaluate the sustainability of a certain building.

Amado and Poggi (2014) created a methodology based on a combination of commercial tools to verify the energy balance of a city by subdividing it in delimited areas and alluding to atoms through considering that these urban units behave as positive, negative or neutral regarding energy use and potential of solar generation. The proposed model is integrated with Geographical Information System (GIS) and is developed to support urban planning in terms of solar energy.

Azhar et al. (2010) evaluated the use of BIM for sustainable projects by comparing pre-construction data (calculations conducted in non-BIM software) with building operation data (using BIM model data) to inform the project owner company on how the operation of the project was going compared to predictions. They analyze annual heating and cooling loads, use of natural gas and electricity, CO2 emissions and the effect of shading devices on solar radiation.

Azhar et al. (2011) created a conceptual framework relating the various LEED credits and sustainability analysis conducted within BIM environments based on literature review and data obtained from industry professionals through interviews. They aimed at displaying in which project phase documentation can be prepared and which LEED credits can be explored with the support of BIM tools. Validation is performed with an example using IES-VE software.

Biswas and Krishnamurti (2012) explore the extension of COBie information exchange format's data structure as a way of fulfilling the needs imposed by green construction classification systems. They validate the proposed extension with a simple example by verifying LEED's Erosion and Sedimentation Control, Development Density and Community Connection credits and automatically creating filled LEED documentation templates.

Inyim et al. (2014) evaluated and optimized a construction project through development of a system based on three criteria collectively: time, cost and environmental impact (CO2 emissions). The Revit plugin tool benefits the AEC industry by utilizing and extending BIM capacity during design and construction phases through consideration of a vast number of possible combinations of components and materials (user-defined) before selecting the alternative that best fits the interests of a certain project. They take advantage of multi-objective genetic algorithm to determine the possible combinations and achieve the closest to optimal result.

Jrade and Jalaei (2013) aimed at allowing designers to have a vision of how sustainable the project they are designing is in real time during the conceptual development stage, conducting Life

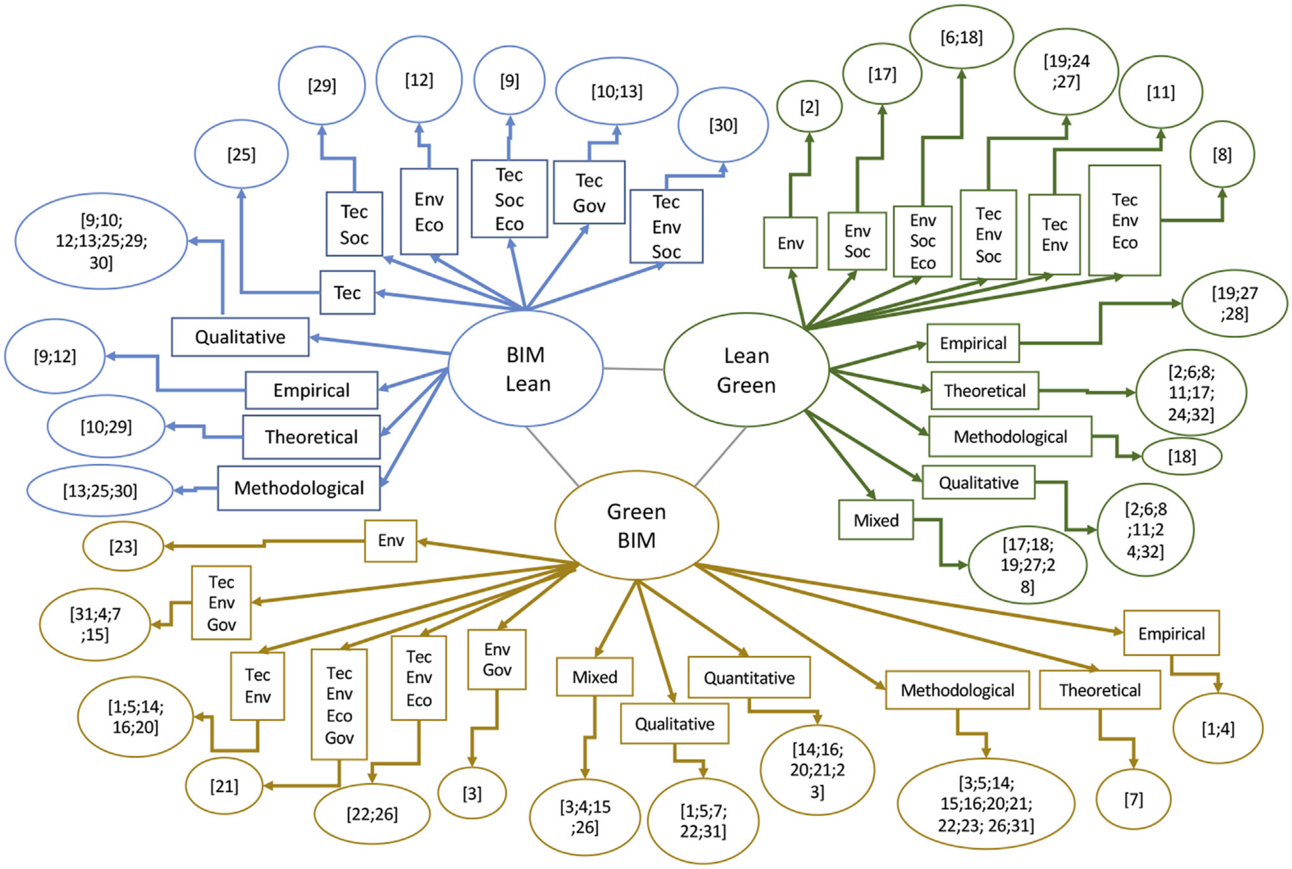

Fig. 4. Thematic synthesis of the literature review.

Cycle Analysis (LCA) by exporting Bills of Materials (BOMs) to identify the effects of component selection on indicators and analyzing the cost of using green materials in the design process in a case study.

Jalaei and Jrade (2015) continued their previous research seeking to integrate a plugin into a BIM tool to estimate through inserted data the "soft cost", which considers costs of project, commissioning, documentation, energy modeling, certification and registry to obtain LEED (New Construction) certification and automate the process of identifying the number of required points based on the selection of LEED categories, suggesting the most adequate level of certification. They also present an external database approach of materials and assembly groups that when integrated with the BIM model allows the designer to better understand the impacts of his decision regarding the environment and LEED in real time.

Li et al. (2012) explored a computational model to calculate carbon emissions during the life cycle of a building with the support of functionalities allowed by BIM methodology that aims to fulfill a gap in tools to estimate CO2 during construction phase. The system takes advantage of a material database embedded in software BEES and the authors categorize emissions in direct (fuel), indirect (electricity) and others (materials and waste). Emissions are accounted for material production, material transport, construction process, operation and waste recycling.

Liu et al. (2015) explored the literature to find the most used optimization processes for construction projects previously researched and then proposed a BIM based optimization method with the objective of improving construction sustainability by integrating BIM simulation and Particle Swarm Optimization (PSO) systems to support decision making at the early stages of projects. The algorithm considers different possibilities of wall types, window to wall ratios, glazing types, external sunshade and building orientation and by considering all combinations determines the optimal one within that scope. The methodology is validated through a case study in which 30% reduction of both Life Cycle Costs (LCC) and Life Cycle CO2 Emissions (LCCE) is achieved.

Oti and Tizani (2015) created a modeling framework by developing a BIM based plugin to support the decision making process during conceptual design of structural systems through multi-attribute analysis, incorporating LCC, carbon footprint and ecological footprint (economic and environmental pillars of sustainability) indicators. They deeply explain the implementation process, requirements and algorithms used to conduct the study.

Motawa and Carter (2013) investigated the viability of applying the BIM approach within Scotland's public department to adopt Post-Occupancy Evaluations (POEs) for more efficient constructions through interviews with department professionals that collect data from the current POE process. They also developed an initial ontology required for energetic assessments of edifications, including climate data, construction specification, site details and energy assessment.

Nguyen et al. (2010) developed a general framework of sustainability evaluation based on LEED certification for an architectural design taking advantage of BIM functionalities to extract model data required for the assessment. The framework basically counts the number of points that would be obtained based on components present in the project. They also implemented this framework taking advantage of Revit's Application Programming Interface (API) even though this was not clearly explicit in the

Table 4
BIM-lean findings from the literature.

B/C/P	Findings	References
Benefit	Automated generation of drawings partly enables review and production to be performed in smaller batches because the information can be provided on demand	(Gerber et al., 2010)
Benefit	Direct transfer of fabrication instructions to numerically–controlled machinery eliminates opportunities for human error in transcribing information	(Gerber et al., 2010)
Benefit	BIM allows analysis of construction activities and hazards to be identified and some of these risks mitigated, such as shortening of construction schedules and the increased value of welding teams via reduction of idle time necessary to avoid dangerous conflicts	(Gerber et al., 2010)
Benefit	Reviewed studies were advancements because they delivered added value to the client and significantly reduced material, time and financial wastes	(Gerber et al., 2010)
Benefit	BIM eases understanding of projects to workers by providing better visualization than traditional 2D drawings and the improved process transparency can make workers more engaged	(Clemente and Cachadinha, 2013), (Sacks et al., 2009)
Benefit	Most lean construction principles have parallel functionalities in BIM methodology	(Clemente and Cachadinha, 2013)
Benefit	Sometimes lean construction principles are not even initially explicitly modeled, but they end up appearing whenever BIM methodology is implemented, thus confirming the existence of strong synergy	(Gerber et al., 2010), (Clemente and Cachadinha, 2013)
Benefit	The link between BIM functionalities and lean construction principles can promote an informed use of BIM for the AEC industry	(Oskouie et al., 2012), (Sacks et al., 2010)
Challenge	Most important feature of BIM is the structured, centralized, defined, easy access and exchangeable information, and not 3D modeling	(Hamdi and Leite, 2012), (Sacks et al., 2009)
Challenge	3D models in the construction process allow not only activity status visualization but also provide decision support to achieve stable flows and communicate Kanban based pull flow signals	(Sacks et al., 2009)
Challenge	BIM proved to be a great asset to facilitate lean construction practices	(Clemente and Cachadinha, 2013)
Challenge	Conceptual analysis of BIM and lean construction indicates synergies from the design phase to delivery and operation	(Dave et al., 2011)
Challenge	Most efforts in the area tend to focus on the project and construction scheduling stages	(Sacks et al., 2009)
Challenge	There is a growing interest in exploring BIM for facility management practices to minimize maintenance and expansion related costs	(Oskouie et al., 2012)
Challenge	The deepness of the relation implies that any organization experiencing a lean journey should consider the use of BIM to leverage results and vice versa	(Sacks et al., 2010)
Challenge	One member of each team should be designated to update the model regularly since this demands time	(Clemente and Cachadinha, 2013)
Challenge	Experience of stakeholders is key to optimize the use of BIM functionalities to serve lean practices	(Hamdi and Leite, 2012)
Challenge	Live links between the BIM platform and information management systems are fundamental	(Sacks et al., 2009)
Challenge	For comprehensive realization of the benefits BIM-lean integration can provide, a deep understand of the production theory is required	(Sacks et al., 2010)
Challenge	BIM can contribute but its adoption is not impeditive for lean construction implementation	(Novak, 2012)
Challenge	Acceptance of yet another system to be used by workers may present a challenge for adoption	(Dave et al., 2011)
Challenge	Application of BIM based lean construction systems requires to firstly develop a robust software capable of supporting the whole life cycle of a project	(Sacks et al., 2009)
Challenge	More research is required on how to present simple and intuitive interfaces to users and how to send updated information to the construction site	(Sacks et al., 2009)
Challenge	Exponential improvements of hardware and software are making the use of BIM in the field a reality	(Dave et al., 2011)
Problem	Lean construction and BIM areas have recently been extensively researched individually but little has been studied regarding the effects of their combination	(Sacks et al., 2010)
Problem	Many researchers focused the application of BIM and lean during design and construction but little has been explored regarding how they can support operation and maintenance	(Oskouie et al., 2012)
Problem	Construction management craves for this types of tool (BIM based lean tools) since the complexity of the construction process makes it difficult for participants to have a clear mental image of what is happening and what needs to be done	(Sacks et al., 2009)
Problem	In the current state of BIM and lean it is likely that most organizations are still experiencing the learning curve, thus, parallel adoption must be taken in small steps	(Sacks et al., 2010)
Problem	Interactions are complex and not the sum of single parts, which is why expert knowledge is not enough to determine all interactions, some will only appear through practical exploration	(Sacks et al., 2010)
Problem	Selection of lean practices to be implemented in a project should be based on the companies BIM maturity level, since if a certain maturity is not achieved, lean practices implementation may not work as expected. It might be a good strategy to previously define the desired benefits and incrementally proceed to obtain more positive correlations	(Hamdi and Leite, 2012), (Sacks et al., 2010)
Problem	Interoperability between BIM software tools is still the greatest barrier for its full implementation	(Dave et al., 2011)
Problem	The lack of capacitated professionals is a barrier for BIM implementation to support lean practices	(Dave et al., 2011), (Clemente and Cachadinha, 2013)
Problem	High software/hardware initial investment requirement is one of BIM's main adoption barriers	(Clemente and Cachadinha, 2013)
Problem	It is difficult to establish a link with models that are still undergoing modifications	(Dave et al., 2011)
Problem	BIM functionalities are still not as explored as they should, e.g. use of BIM technologies is presently still limited to clash detections and 4D	(Oskouie et al., 2012), (Dave et al., 2011)
Problem	With the increasing mitigation of the various barriers still preventing wider implementation of BIM, the industry will perceive a bigger leverage of these tools to support lean practices	(Gerber et al., 2010)

research and validated the methodology on a residential case study.

Salgueiro and Ferries (2015) identified environmental certification criteria that can be evaluated during the schematic design phase, clearing out which ones can be automatically (5) or partly automatically (5) obtained, and described activities and information exchanges through a process map (adapted from Eastman et al. (2011)). They also compared criteria from LEED and BREEAM trying to find equivalences and identified which commercial tools were capable of supporting each criteria.

Table 5 presents the main conclusions found by the authors after conducting their researches, also referencing where each finding can be encountered in the literature.

3.2.3. *Lean and green*

Garza-Reyes (2015) explored through a systematic review of the literature, studies regarding the integration of lean and green topics identifying gaps and inconsistencies in the literature besides developing guidelines for future research over a table populated with questions that need to be answered.

Bae and Kim (2007) qualitatively examined within the literature how certain currently applied lean construction methods can contribute/impact to each pillar of sustainability on high performance edifications by developing a framework of relationship and how these methods evolve to pitch in on greener constructions. They also cite better types of contracts and delivery methods to support sustainable constructions.

Carneiro et al. (2012) analyzed, based on the fact that sustainability guidelines consider all stages of the lifecycle of a building and that LEED does the same, the complementarity between the lean and green through an interrelationship matrix of interactions between LEED certification guidelines and lean construction principles.

Dues et al. (2013) identified synergies, differences and complementarities of lean and green whilst not focusing on any specific industry, basically looking to expose potential areas in which companies can integrate green in their current business practices. They also develop a framework that contrasts conceptual differences as well as situations in which they overlap.

Koranda et al. (2012) investigated the relationship and applicability of sustainability and lean concepts on six small construction projects during execution stage and also developed a framework to aid this implementation on future projects, envisioning to make this relationship a prevailing practice. They also explain the influence of implementing certain LEED credits on lean concepts application.

Kurdve et al. (2015) conducted a literature review on operations and environmental management to understand improvement tools and principles and identify the gaps and needs in current practices. They then explored how these could be integrated on an operational level and include the waste management supply chain by proposing a Waste Flow Mapping (WFM) method later applied on a case study comprised of a set of manufacturing sites. The method combines lean manufacturing tools (VSM) with clean production strategies and material flow cost accounting to examine material waste flows, costs, material efficiency and operational efficiency. The key indicator of the method is material efficiency (product weight/total received weight).

Lapinski et al. (2006) evaluated, using a scientific approach, the lifecycle of the delivery process of a Toyota construction to understand critical activities and capacities that leveraged the success of the project, identifying where value and waste were generated. They verified Toyota was able to obtain a LEED gold certificate without cost increases usually observed between 5% and 10%. The process map analysis showed Toyota employed the following lean processes: decision to adopt sustainable objectives early in the project, alignment of sustainable objectives with the business case of the project, identification and search of features that naturally aligned with sustainability, selection of experienced design and construction teams beforehand, time investment in aligning individual and project objectives.

Novak (2012) explored the synergy between lean construction and sustainability focusing on the concept of value generation on the construction process by conducting interviews and surveys with owners and contractors of three different construction sites supported by the fact that this is a contemporaneous subject. All three studied exhibited patterns that indicate a strong correlation between lean and sustainability. Participants of one specific study actively leveraged the synergy that the integrated process of lean offers to the delivery of sustainability, also understanding a link between value from the project perspective and global sustainability perspective.

Rosenbaum et al. (2014) conducted a diagnosis of the constructive process of walls of a case study by proposing an improved adaptation of the lean tool Value Stream Mapping (VSM), which analyses the complete flow of a production unit, describing various productivity and sustainability indicators applicable on construction processes. Improvements in the method seek to considerably reduce wastes by synchronizing production with client needs.

Table 6 presents the main conclusions found by the authors after conducting their researches, also referencing where each finding can be encountered in the literature.

4. Discussions

Key synergies emerging from the systematic literature review are detailed below, including what the authors refer to as a BIM, Lean and Green integration matrix. The authors first present the overall findings on the relationship between BIM, lean and green, followed by a discussion of specific BIM-lean interactions that impact environmental, economic and social streams of sustainability such as resource waste, energy analysis, emissions, material depletion, workers safety, cost estimation, performance monitoring and information sharing. The authors then synthesize the positive and negative impacts of BIM and lean on sustainability work streams through the BIM, lean and green integration matrix.

4.1. Relationship between BIM, lean and green practices

Research findings state that there is still large unexploited potential for both operational and technological improvements as well as cleaner production and eco-efficient processes in the AEC industry. As observed in the literature, the systematic and integrated use of BIM and lean construction has the potential to ease the sustainable pressures and improve productivity.

Nowadays, there is a growing interest in the alignment of BIM technologies and lean management philosophy, but most organizations are still at the beginning of the learning curve. Their parallel adoption seems to be quite promising, providing better visualization of processes, clear communication and fast information flow, minimization of risks, maintenance and human error and helping in decision making. Although BIM can facilitate lean construction practices and most lean principles have parallel functionalities in Building Information Modeling, BIM based lean tools require experienced, trained and engaged stakeholders, integrated and constantly up-to-date interoperable information systems, investment in equipment and technologies, and user-friendly interfaces.

A number of lean based principles, strategies and management methods related to: eliminate waste; establish value stream; encourage flow; pull production; and pursue perfection could be used in a complementary way with Building information modeling. However, a deep understand of the production theory is required to fully achieve the benefits of BIM-lean integration and the link between BIM functionalities and lean construction principles must be taken in small steps. In addition, in order to reach a higher step, the construction industry should invest in knowledge management through a holistic education, training, research and innovation led to building soft, technical and technological skills respectively about green, lean and BIM.

As Marzouk and Othman (2017) stated, some advantages of utilizing BIM are that it can be used throughout all project life cycle stages, can aid the sector's stakeholders in enforcing the system's sustainability, it is a very useful instrument for auditing and calculating the heat loss/gain against various design alternatives and different conditions and it helps to assess and compare the energy performance of buildings, regarding the eco-efficiency impact of design. Furthermore, BIM simplifies the understanding of projects, provides the possibility of multi-skilled teams to work

Table 5
BIM-green findings from the literature.

B/C/P	Findings	References
Benefit	Use of BIM based sustainability assessment tools saves significant time and resources by generating results very quickly when compared to traditional methods (not quantified on this study}	(Azhar et al., 2010), (Azhar et al., 2011)
Benefit	BIM based sustainability assessment results are accurate. This was found by comparing pre-construction evaluations based on CAD tools and post-construction assessments generated with the aid of an as-built BIM model	(Azhar et al., 2010)
Benefit	Evaluation of sustainable projects require information that is aggregated during the different phases of a project and construction lifecycle information. This is usually fragmented as a consequence of being generated by different teams with different purposes. BIM provides an opportunity to integrate teams and information in a single central model	(Biswas and Krishnamurti, 2012), (Motawa and Carter, 2013)
Benefit	The complexity of construction makes it difficult to consider a multi-objective decision and BIM is presently the best available methodology and platform to aid this process	(Inyim et al., 2014)
Benefit	BIM as an asset for green buildings supports deeper exploration of preliminary designs, providing the ability to conduct rapid and early assessments and allowing iterative optimization processes of projects to support decision making for better performance of constructions	(Jrade and Jalaei, 2013), (Jalaei and Jrade, 2015), (Liu et al., 2015), (Salgueiro and Ferries, 2015)
Benefit	BIM has Information and Communication Technologies (ICTs) that allow the various stakeholders to collaborate during the whole lifecycle of a building	(Motawa and Carter, 2013)
Benefit	Intelligent information created by a BIM model can conduct whole-building energy analysis, simulate performance, and visualize appearance. It also provides building designers with direct feedback to test the design in order to improve building performance over the lifecycle of the edification	(Motawa and Carter, 2013)
Benefit	The development of Green BIM tools which integrates the design model and the simulation can analyze multi-disciplinary information in a single model which improves the analysis and eliminates errors of data handling	(Azhar et al., 2011)
Benefit	It is essential to conduct sustainability analysis in parallel with project development as early as possible to allow building performance decision making that impacts less, and BIM can support this process	(Alwan et al., 2015), (Azhar et al., 2011), (Liu et al., 2015)
Benefit	To achieve CO2 goals, better performance monitoring and information sharing are required from the moment the project is delivered, and BIM provides the necessary technology	(Motawa and Carter, 2013)
Benefit	Stakeholder integration and collaboration is essential for the development of sustainable projects and BIM eases this complex process	(Biswas and Krishnamurti, 2012), (Alwan et al., 2015)
Benefit	The best presently available format for BIM systems model information exchange to support sustainability analysis is gbXML	(Alwan et al., 2015), (Azhar et al., 2011)
Benefit	Software IES-VE is the most versatile and powerful commercial sustainability assessment tool among the three explored (Ecotect, Green Building Studio, IES-VE) according to industry professionals	(Azhar et al., 2011)
Challenge	Previous research demonstrate the viability of semi-automated assessments with BIM tools	(Biswas and Krishnamurti, 2012)
Challenge	Inclusion of environmental impacts in the optimization process facilitates the integration of green construction concepts in traditional practices	(Inyim et al., 2014)
Challenge	The integration of BIM and sustainability principles has the potential of altering traditional practices to produce high performance projects	(Jalaei and Jrade, 2015)
Challenge	By identifying the Level of Development (LOD) required for certain sustainable certification criteria to be met it was possible to verify the pressure imposed by sustainability measures to focus on the conceptual design and that the initial project phase presents the best stage to make sustainability related decisions	(Salgueiro and Ferries, 2015), (Oti and Tizani, 2015)
Challenge	LEED is presently the leading and most widely adopted certification system in the USA and internationally	(Jalaei and Jrade, 2015), (Nguyen et al., 2010)
Challenge	Results show 17 credits and 2 pre-requisites (total of 38 points) from LEED can be directly or indirectly prepared with support of BIM tools, thus proving an integration of BIM and LEED is possible but not without restrictions	(Azhar et al., 2011), (Jalaei and Jrade, 2015)
Challenge	BIM is interesting for designers to know in real time how their decisions are impacting the projects regarding environmental impacts and LEED certification possibility	(Jrade and Jalaei, 2013)
Challenge	Three categories of LEED have direct relation with BIM: materials selection and use, systems analysis, and site selection and management	(Jalaei and Jrade, 2015),
Challenge	There are three types of LEED credit influences in a project: those that do not add costs, those that do but have rapid return, and those that have late return or no return	(Nguyen et al., 2010)
Challenge	It is not only viable but necessary to implement efficient energy models in new and existing urban areas	(Amado and Poggi, 2014)
Challenge	The construction sector is the biggest responsible for CO2 emissions, which is the dominant gas emitted by human activity, thus, it should always be considered when analyzing environmental impacts	(Li et al., 2012), (Oti and Tizani, 2015)
Challenge	CO2 emissions provide a basis for decision-making process regarding environmental impact	(Li et al., 2012)
Challenge	Genetic algorithms are capable of handling the large amount of data found in the construction industry	(Inyim et al., 2014)
Challenge	Relative assessments instead of absolute as the ones presented by certification systems can be a great asset to find best solutions for certain projects	(Oti and Tizani, 2015)
Challenge	The complexity of the construction industry calls for a multiobjective analysis because it is not possible to consider the number of different options manually mainly due to the time required for calculations. It is possible to conduct such analysis with the goal of minimizing Life Cycle Costs (LCC) and Life Cycle Carbon Emissions (LCCE), which are considered important indicators to measure construction sustainability	(Liu et al., 2015), (Oti and Tizani, 2015)
Challenge	Use of real data obtained from site with sensors enables a more accurate analysis	(Motawa and Carter, 2013)
Challenge	The field of performance indicators is the most researched within the sustainability domain	(Oti and Tizani, 2015)
Challenge	A macro view of renewable energy systems creates opportunities to redirect energy from locations with positive balances to others with negative balance through smart grids	(Amado and Poggi, 2014)
Problem	Computer Aided Design (CAD) based sustainability assessments require too much human intervention, making the process not only long and costly, but also more susceptible to errors	(Nguyen et al., 2010)

Table 5 (*continued*)

B/C/P	Findings	References
Problem	BIM for sustainability has been predominantly explored to support design and construction, and only a small number of studies target the post-occupancy phase	(Motawa and Carter, 2013)
Problem	It is possible to conduct LEED based assessments with data extracted from a BIM model, but there is no one-to-one direct relationship between LEED credits and BIM analysis	(Alwan et al., 2015), (Azhar et al., 2011)
Problem	Incompatibilities were found comparing results obtained in the traditional way caused by outdated BIM models	(Azhar et al., 2011)
Problem	The construction industry is the main villain of sustainable development due to all impacts it causes	(Nguyen et al., 2010)
Problem	There is no available tool that dynamically calculates CO2 emissions during construction	(Li et al., 2012)
Problem	Due to construction industry complexity, there is a need to create ways to evaluate construction status and compare it with benchmarks	(Li et al., 2012)
Problem	Little has been researched on decision support regarding greener constructions for structural projects	(Oti and Tizani, 2015)
Problem	The small number of reported experiments targeting sustainability assessment of the structural system was conducted only after construction finished, thus hindering changes	(Oti and Tizani, 2015)
Problem	Information contained in BIM models that can aid sustainability assessments is still limited, thus a significant portion of information needs to be input manually and in many cases the process can only be partially automated, taking away some of BIM's most important features: automation and non-requirement of user interference	(Alwan et al., 2015), (Azhar et al., 2010)
Problem	Mechanical community is still resistant to BIM adoption since certifications such as Title 24 (California Energy Commission standard) still approve and encourage use of non-BIM software	(Azhar et al., 2010)
Problem	BIM based systems still lack interoperability, therefore designer intervention is still imperative	(Azhar et al., 2010), (Salgueiro and Ferries, 2015)
Problem	IFC and gbXML are exchange formats that presently are not able to provide the necessary content required for classification systems (LEED, BREEAM, etc.) but are extensible	(Biswas and Krishnamurti, 2012)
Problem	Conversion to COBie format is based on the IFC file exported and not only is information partially lost when translating BIM models but also the flow is unidirectional	(Biswas and Krishnamurti, 2012)
Problem	Data exchange to sustainability tools is unidirectional, thus simulation tools are not able to feed data back to BIM platforms	(Motawa and Carter, 2013)
Problem	Despite the capacity of BIM to allow designers to compare different project alternatives and generate quantitative data volumes, there is still no interface or software to organize and classify this data to ease multicriteria assessments and support the decision making process	(Salgueiro and Ferries, 2015)

at the same time and can guide workers on how to perform certain activities in the best way following company standards. Besides that, it provides live connections with partner (supply chain) databases which significantly decreases waiting time, thus improving flow.

In addition, regarding the use of BIM focused on sustainability, it is observed that BIM not only brings technical benefits to the project, but provides a live and active interface and improves process transparency. Thus, BIM also acts as an innovative and integrated working platform that ensures that only the correct materials and accurate components are produced throughout the project life cycle and eliminate production and environmental waste, reduce energy use, transport emissions and resource depletion.

Moreover, more than reach cost reduction and failures correction, lean and green approaches seek to reduce wastes, lead time and use various techniques such as VSM and LCA to manage supply chain, organizations and people. It is noticed that lean can facilitate sustainability, reducing ecological impacts, pollution and unnecessary usage of resources, integrating people towards delivering greener products and services. However, while lean is more geared towards production waste, being more concerned with employees and customers, green is more geared towards environmental waste, seeking the well-being of all stakeholders in the long term. Hence, these are complementary approaches as Green lean initiatives could provide a holistic project-based orientation aimed to continuous improvement with efficiency, effectiveness and ethics in the long term.

In our view, there is still a lack of attention from both academia and industry in the benefits of the integration of BIM, green and lean. Therefore, it is essential to investigate other methods or technologies of manufacturing in order to reduce greenhouse gases, to measure the carbon footprint and especially to use a more holistic approach to reach a broader sustainable scope and bring multiple benefits to more stakeholders during construction project life cycle. The green BIM-lean integration can encourage the simultaneous assessment of production and environmental variables. Our paper presents some synergies of BIM, green and lean and balance benefits, problems and challenges with using the three concepts within the AEC industry.

4.2. BIM, Lean and green integration

Table 7 highlights and explains the main interactions that could be perceived by literature review of theoretical, empirical and methodological studies regarding combinations of BIM, Lean and Sustainability aspects. Then, in Table 8, it is shown the BIM, Lean and Green integration matrix, in which colored-only cells represent positive (grey) and negative (yellow) BIM and lean integrations as perceived by Sacks et al. (2010). Numbered cells represent positive (green) and negative (orange and between parenthesis) BIM, lean and sustainability interactions in the authors view. In addition, Tables A9 and A10 explain row and column keys. The matrix enables a comprehensive approach to sustainable management in construction projects. However, it is seen that the effective adoption of BIM and lean for sustainability depends on proactive organizations willing to invest and believe in change rather than using ad-hoc solutions. Moreover, it is important that there are sustainable measures and indicators to evaluate the performance of lean methods and BIM tools for sustainability.

The review results have also shown that substantial efforts are suggested to reach mutually agreeable, practical and long-term solutions for sustainable construction. Sustainable construction developments require intensive interdisciplinary collaboration and the involvement of all stakeholders in order to add more value to the project. Moreover, an important requirement is to have a collaborative project process to enable quick design changes and fast re-evaluation of structural, thermal and energy analyses; cost estimations; and conformance to client values.

In this way, Building Information Modeling not only requires

Table 6
Green-lean findings from the literature.

B/C/P	Findings	References
Benefit	Lean construction is the ideal approach to leverage sustainability value and integrate the delivery process by providing the foundation for sustainable delivery	(Novak, 2012)
Benefit	Using a lean-green approach will allow managers to more easily glimpse improvement opportunities and propose realistic implementation plans, considering that integration can be implemented more easily if priorities are well defined beforehand	(Rosenbaum et al., 2014), (Koranda et al., 2012)
Benefit	Lean economic improvement potentials coincided with environmental ones in this study (e.g. transport route reduction)	(Kurdve et al., 2015)
Benefit	Previous studies identified lean and green integration as the best approach to minimize the environmental impacts of production	(Kurdve et al., 2015)
Benefit	Studies of correlations concentrate in five main areas: compatibility, integration, integration followed by case study, proposal of method/indicator of performance assessment, organization performance impact and application or empirical research on (which accounts for two articles that study this integration in the construction industry)	(Garza-Reyes, 2015)
Benefit	Waste classification is one of the most important approaches of the construction industry regarding environmental impacts	(Kurdve et al., 2015)
Benefit	Economic impacts of lean implementation are: initial cost reduction, resource reduction, operational cost reduction and high performance capacity. Only recently these have started to be exploited	(Bae and Kim, 2007), (Lapinski et al., 2006)
Benefit	Social impacts of lean implementation are: work space security, occupant health, community well-being, participants loyalty and improved external image	(Bae and Kim, 2007)
Benefit	Environmental impacts of lean implementation are: reduction of resource depletion, pollution prevention by waste elimination and resource preservation	(Bae and Kim, 2007)
Benefit	Value Stream Mapping (VSM) and Life-Cycle Assessment (LCA) are the main lean and green tools, respectively	(Dues et al., 2013)
Benefit	Toyota was able to reach better green project results without going through LEED certification	(Koranda et al., 2012)
Benefit	To better understand their integration it is necessary to understand the attributes that distinguish between the two paradigms, and consider that there are different interpretations on how to use lean principles to support environmental challenges	(Dues et al., 2013), (Kurdve et al., 2015)
Benefit	There is presently no financial incentive to generate value on a project and lean can only contribute to sustainability if the client values it. This way, important features to the client (space, functionalities, aesthetics, image, price) and to the environment (minimum impact, system efficiency, healthy and productive environment) need to be considered as "values", but historically little effort is put on considering client requirements and necessities	(Lapinski et al., 2006), (Bae and Kim, 2007), (Rosenbaum et al., 2014), (Novak, 2012)
Challenge	They share common tools and practices and overlap on: waste and waste reduction techniques, people and organization, security, lead time reduction, supply chain relationship, efficiency, productivity, service level KPI	(Dues et al., 2013), (Koranda et al., 2012)
Challenge	Some contracts and lean construction delivery methods are better than others to support sustainability. The ideal contractual model is Design-Build (DB) because it integrates contractor and designers earlier in the project	(Bae and Kim, 2007), (Koranda et al., 2012)
Challenge	Most lean construction studies focused specifically on the waste effects of poor planning of the construction process	(Lapinski et al., 2006),
Challenge	Construction performance is highly impacted by project constructability	(Rosenbaum et al., 2014)
Challenge	Lean thinking is concerned with initial cost reduction, but shows no effective concern in reducing wastes to favor the environment. It often neglects material waste and efficiency, while green construction initiatives usually neglect the economic factor. Green construction approaches are usually focused on the design and operation stages, while lean tends to focus on construction.	(Carneiro et al., 2012), (Rosenbaum et al., 2014), (Kurdve et al., 2015)
Challenge	There are eight main differences (that can be complementarities) between the topics: their focus, what is considered waste, the customer, product design and manufacturing strategy, end of product-life management, Key Performance Indicators (KPIs), the dominant cost, the principal tool used and certain practices (e.g. replenishment frequency of supplies on construction site)	(Dues et al., 2013)
Challenge	During the preparation of the interrelationship matrix some lean construction principles did not dialogue with LEED pre-requisites and credits due to conceptual differences, since LEED mainly focuses on design conception while lean construction basically focuses on the execution phase	(Carneiro et al., 2012)
Challenge	Considering all LEED criteria and lean construction principles, 473 combinations would be possible but only 60 intersections were found even though both target waste reduction and improved construction performance, but even though a small number of interrelations was found, lean construction and LEED philosophies can be implemented complementarily	(Carneiro et al., 2012)
Challenge	LEED certification system is an international reference, but its normatively does not provide the flexibility valued by lean construction	(Koranda et al., 2012), (Carneiro et al., 2012)
Challenge	It is harder to consider lean concepts for LEED projects (specially small ones), since delivery time and stay on construction site significantly increase	(Koranda et al., 2012)
Challenge	Despite the possibility of higher initial costs, sustainable constructions may provide significant savings during the lifecycle and at the same time reduce waste during execution, therefore being self-financing	(Lapinski et al., 2006), (Novak, 2012)
Challenge	Communication and involvement of all stakeholders is of unparalleled importance to add value and accomplish a successful project	(Koranda et al., 2012), (Kurdve et al., 2015), (Novak, 2012)
Challenge	Sustainable construction projects require intensive interdisciplinar collaboration, complex design analysis and careful selection of materials particularly early in the project delivery process	(Lapinski et al., 2006),
Challenge	Minimization of activities that do not generate value and use of raw materials is essential for the presented Waste Flow Mapping (WFM) method which proved itself viable to analyze the efficiency potential of material waste	(Kurdve et al., 2015)
Challenge	Visualization of scenario, reliable information sharing, easy comprehension, systematic and fast approaches are key points for lean tools	(Kurdve et al., 2015)
Challenge	Despite the existence of synergies and complementarity opportunities, there are also conflicts between principles (lean and green have different visions on the meaning of waste), which means some companies will have to compromise the application of certain lean practices to achieve a better level of sustainability,	(Dues et al., 2013), (Koranda et al., 2012)

Table 6 (*continued*)

B/C/P	Findings	References
	e.g. lean practices do not necessarily reduce CO2 emissions (Just in Time (JIT) is an example that usually causes the exact opposite)	
Challenge	Lean practices envision the environment as a valuable resource, while green practices see it as a constraint for designing and producing product and services	(Dues et al., 2013)
Problem	Little has been researched and there is a limited number of approaches or models that integrate sustainability and lean thinking and merge their elements and principles in AEC. Individually, both have been extensively explored for sustainable buildings	(Lapinski et al., 2006), (Garza-Reyes, 2015)
Problem	There are articles that seek to integrate lean and green with various areas (BIM is not one of these) but integration between lean improvement and environmental assessment methods are rarely achieved	(Garza-Reyes, 2015), (Kurdve et al., 2015)
Problem	The construction industry is historically among the worst in terms of use of resources, productivity and pollution management, e.g. its approach to defects is rework	(Rosenbaum et al., 2014), (Koranda et al., 2012)
Problem	The construction industry traditionally disaggregates the whole in the sum of its parts, turning them into fragmented and isolated parts, which results in cost increases, delays and quality decline	(Novak, 2012), (Rosenbaum et al., 2014)
Problem	There is no clear/obvious way in which lean construction principles and LEED credits relate since LEED does not directly support time and cost reduction because its focus is not on process improvements	(Carneiro et al., 2012)
Problem	Value generation must be thought in terms of society problems, consequently the environment, and sustainability should identify labor inefficiency as a waste	(Novak, 2012), (Koranda et al., 2012)
Problem	Many owners and design teams make mistakes at the beginning due to inexperience on unique and challenging requirements of green constructions, thus assessments usually require know-how in environmental management of participants	(Lapinski et al., 2006), (Kurdve et al., 2015), (Koranda et al., 2012)
Problem	Productivity and environmental performance are usually treated in isolation, thus, the industry is not exploring the advantages of lean-green synergy	(Rosenbaum et al., 2014)
Problem	Only a small number of tools have been developed targeting production managers and environmental engineers	(Kurdve et al., 2015)
Problem	Design and construction team selection not conducted simultaneously usually generate delays. Also, excessive number of subcontractors causes bidding delays, excessive rework, reduction in scale economy and lack of integration	(Lapinski et al., 2006)
Problem	Many studies explore the correlation of green constructions and lean practices on the perspective of waste reduction, but the fact that many lean tools only seek to reduce waste, implies they are not taking advantage of its full potential	(Novak, 2012)
Problem	In many cases green construction is only envisioned in terms of criteria of certifications such as LEED and not in the context of the Triple Bottom Line (TBL) but LEED certification creates barriers to implement sustainable objectives that are not within its scope, despite drawing attention to greener edifications	(Novak, 2012)

this integration of stakeholders, but increases flexibility by using model data to iteratively run various and more detailed sustainability analyses within different design alternatives without deeply compromising setup time. BIM significantly reduces activity and equipment conflicts in time and space (temporal clash detection), improves worker safety, increases efficiency and reduces schedule variability and cycle times (production duration) during the construction. In addition, BIM provides better appreciation of design at early stages due to its capability of fast generating of multiple design alternatives which avoid rework, pollution and material depletion (environmental impact), resource waste (purchase of materials not included in the budget), and even uncommitted workers, affecting productivity and product quality. This also enables early sustainability assessments against performance criteria (e.g. energy) and, thus, earlier design adjustments.

On the other hand, it is clear that lean methods (e.g.: employee involvement, quality circles, Six Sigma and pull approach) and lean integrated tools as the Sustainable or green VSM and waste flow mapping have positive impacts on improving environmental performance (Caldera et al., 2017). This way, it may facilitate sustainable construction practices. Therefore, BIM and lean approaches generate optimal solution in terms of performance and environmental impact, speeds up decision making processes, reduces delays and consequently financial wastes, thus positively impacting the economic and social aspects of sustainability.

However, integrating these approaches to achieve the sustainability of the construction sector requires: overcoming cultural barriers; collaborative work, through the joint participation of its stakeholders; top management support, with top-down implementation and control strategies; specified standards and regulations, which could completely acknowledge global boundaries in a sustainable and pragmatic way; integrated project management; interoperability between systems; and government incentives. From this, it is also important to use top-down voluntary environmental benchmarking tools, such as BREEAM and LEED in order to encourage the sustainable change and to develop a bottom up leadership model, based on participatory methods and cooperation (Alwan et al., 2017). Besides that, public authorities should invest in incentive policies to point out to corporations the advantages of using integrated BIM with modern management methods such as lean.

Hence, lean methods and BIM technologies can help organizations and governments achieve sustainable development goals using scientific knowledge management to implement goals and monitor their efforts. Lean thinking can be explored as a way for technical expertise and skills to be built, translating goals' bodies of knowledge into policy action to solve global problems. Innovative technologies such as BIM, can support and ensure new ways to bridge the gap between scientific knowledge and decision making by actively assisting leaders. Thus, BIM-lean-green interactions can provide, especially the construction industry, an unprecedented opportunity for problem solving around the main sustainable development challenges.

5. Conclusion

Summarily, this paper structurally explores, through a systematic review, the literature of each pairwise combination of the three concepts (sustainability/green, lean and BIM) studied, reporting findings of each of those combinations, this way showing the strong relationship these fields may present on construction related activities and providing backed knowledge to develop an interrelationship matrix incorporating BIM, lean and sustainability dimensions. The objective was entirely reached with a selection of

Table 7
Interactions explanation.

No	Explanation
1	Because BIM provides better appreciation of design at early stages by rapidly generating multiple design alternatives to conform with client requirements (values), which is a fundamental requirement of sustainability assessments for better functional projects, the quality of the end product is better and accompanies design intent. This reduces the variability that is commonly present due to late changes during construction stage (Jrade and Jalaei, 2013; Jalaei and Jrade, 2015), (Liu et al., 2015; Salgueiro and Ferries, 2015)
2	Data extracted from BIM models allows re-use for predictive design testing against performance criteria (such as thermal, energy, acoustics, etc) thus ensuring it is appropriate for the designated function which consequently reduces variability and improves product quality (Li et al., 2012; Biswas and Krishnamurti, 2012; Amado and Poggi, 2014; Jalaei and Jrade, 2015)
3	BIM provides a solution for traditional 2D drawing and specification's limitations of needing to represent a single object in multiple places which in turn makes it difficult to maintain consistency between information sources when changes are made, by concentrating all information in a single source (the model) from which reports are automatically generated, indirectly impeding wastes on rework that generate more pollution and material depletion (environment), resource waste (economic) and even uncommitted workers (social), which in turn affects productivity and product quality (Gerber et al., 2010; Sacks et al., 2010; Oskouie et al., 2012; Clemente and Cachadinha, 2013)
4	As observed in the findings, sustainable construction developments require intensive interdisciplinar collaboration and involvement of all stakeholders in order to add more value to the project and building modeling imposes a rigor on designers in that flaws or incompletely detailed parts are easily observed or caught in clash checking or other automated checking that if done manually would require intensive mental work, iterations and time, and would not be able to find predict all problems. This improves design quality, reduces cycle times and in turn reduces reworks that generate innumerous wastes and impact the economic and environmental aspects of sustainability (Sacks et al., 2009; Dave et al., 2011; Oskouie et al., 2012; Motawa and Carter, 2013; Clemente and Cachadinha, 2013)
5	4D visualization of construction schedules provided by BIM significantly reduces occurrences of activities and equipment conflicts during construction in time and space, improving worker safety, increasing efficiency, reducing schedule variability and reducing cycle times during construction itself, which in turn may reduce delays and consequently financial wastes, therefore positively impacting the economic and social aspects of sustainability (Lapinski et al., 2006; Bae and Kim, 2007; Novak, 2012; Koranda et al., 2012; Rosenbaum et al., 2014; Kurdve et al., 2015)
6	Direct transfer of instructions for component fabrication to numerically-controlled machinery, diminishes chances for human error and improves possibilities of fabrication of better quality and more complex products, such as "greener" components which are often more difficult to fabricate and demand higher precision (Nguyen et al., 2010)
7	According to Khemlani (2009), this functionality can be said to increase inventory of design alternatives. This can be considered beneficial in terms of making broader selections, delaying selection of a single alternative until the last responsible moment. This is specifically important for sustainability, since the last requires consideration of design alternatives until a close to optimal solution in terms of performance and environmental impact is achieved (Alwan et al., 2015; Azhar et al., 2010)
8	Live connection with partner (supply chain) databases significantly decreases waiting time, thus improving flow. This could be a major gain in terms of sustainability by providing designers the ability to understand during the design process how the presence of certain components is impacting the design in terms of environment and costs. This will provide a possibility for designers to test multiple project combinations on the go (Gerber et al., 2010; Jrade and Jalaei, 2013; Jalaei and Jrade, 2015; Liu et al., 2015; Salgueiro and Ferries, 2015)
9	BIM's provided capability to integrate stakeholders, combined with the requirement of sustainable constructions of having a collaborative project processes to allow quick turn-arounds of structural, thermal, energy analyses; cost estimation; and evaluation of conformance to what the client values, significantly reduces cycle times for building design and detailing, which is also only possible because BIM automates generation of drawings and documents, as designers would hardly go through the process of altering every single document every time a turn-around was made (Nguyen et al., 2010; Liu et al., 2015; Oti and Tizani, 2015)
10	Flexibility is increased by BIM when it allows use of model data to iteratively run various and more detailed sustainability analyses within different design alternatives without deeply compromising setup time, thus contributing to a better design in terms of performance and environment impacts (Azhar et al., 2010; Azhar et al., 2011)
11	By considering the time spent on data entry as setup time, automated numerically controlled machinery drastically reduces if not eliminates setup time, making single piece runs, which are very common on "green" projects, viable (Nguyen et al., 2010)
12	Use of an integrated model in a collaborative work environment enables teams to bring multi-disciplinary knowledge and skills, a requirement of sustainable construction projects, which usually requires know-how of participants in environmental management due to unique challenging points of green constructions (Biswas and Krishnamurti, 2012; Motawa and Carter, 2013)
13	BIM methodology can provide ways of animating the production and assembling sequence, which in turn can guide workers on how to perform certain activities in the best and company standardized way. This is particularly important for sustainable projects because construction processes are much more complex and workers will probably be unfamiliarized with these not so usual tasks. Importance is even bigger for the construction industry because rotation of workers on site is high (Oskouie et al., 2012)
14	Considering platforms in which BIM allows live status reports, measurement of labor inefficiency, which according to Novak (2012) and Koranda et al. (2012) should be considered waste by sustainability, becomes viable and documented, which is directly related and important to achieve continuous process improvements
15	Sustainable construction systems impose increasingly complex designs, making it more and more difficult for even trained professionals to generate proper mental models. BIM significantly simplifies this understanding of projects, providing ground for more complex products (Sacks et al., 2009; Sacks et al., 2010)
16	BIM provides the possibility of multi-skilled teams to work at the same time aiming at generating different design alternatives early during the project process. This is particularly important for sustainable projects to find a near optimal solution without compromising much time (Sacks et al., 2009; Dave et al., 2011)
17	This is specifically a setback because BIM based sustainability assessment technologies are not yet mature enough to be fully automated, thus they cannot be considered reliable technologies (Biswas and Krishnamurti, 2012; Jalaei and Jrade, 2015)
18	For green construction projects, since the 3D model provides a single and understandable source of information, the client can ensure all his requirements (values) are in sync already during conceptual project stage, which is extremely important for sustainable designs and allows other participants to take part in decision making (Azhar et al., 2011; Jrade and Jalaei, 2013)
19	At the conceptual stage, quick adaptations to prepare cost estimates and sustainability related assessments (energy, lightning, etc) allows evaluation of multiple alternatives of design, including use of optimization algorithms such as genetic algorithms, as proposed by Inyim et al. (2014)
20	Simulations allowed by intelligence built in the model objects viabilize automatic checking against sustainability regulations, improving efficiency of verifications and validations (Azhar et al., 2011; Biswas and Krishnamurti, 2012; Inyim et al., 2014)
21	These functions facilitate collaborative decision making by providing transparent information to involved teams and increasing the number of options to be considered. This is particularly interesting for sustainable projects, which always seek near optimal building performance related solutions thus requiring multiple alternatives consideration (Motawa and Carter, 2013; (Salgueiro and Ferries, 2015)

32 articles, which allowed the proposed matrix. The key points of the bibliometric analysis were the following: the year that has the larger number of articles published about the theme was 2012; the most relevant journal was Journal of Cleaner Production; the countries with the largest volume of published articles were United States and the United Kingdom; the preferred methodology within the analyzed studies was qualitative, specially empirical studies.

Despite the lack of researches that explore collectively all three concepts, this paper provides understanding that there is clearly a strong synergy between these by identifying and explaining 21

Table 8
BIM, Lean and Green integration matrix.

Lean Principles & BIM Functionalities		Reduce variability		Reduce cycle times		Reduce batch sizes	Increase flexibility		Select na appropriate production control approach		Standardize	Institute continuous improvement	Use visual management			Design the production system for flow and value			Ensure comprehensive requirements caputre	Focus on concept selection	Ensure requirements flowdown	Verify and validate	Go and see for yourself	Decide by consensus consider all options	Cultivate na extended network of partners
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**	**T**	**U**	**V**	**W**	**X**
Visualization of form	**1**	1													15				18					18	
Rapid generation of design alternatives	**2**	1		9			10									16				19				21	
Re-use of model data for predictive analysis	**3**	2	2	9			10												1	19		20		21	
	4			9												16				19					
	5	1	1	9															1	1	1	20		21	
Maintenance of information and design model integrity	**6**	3	3																						
	7	3	3	4													4					3			
Automated generation of drawings and documents	**8**	3		9																					
Collaboration in design and construction	**9**															16									
	10	4		9				12																21	
Rapid generation and evaluation of multiple construction plan alternatives	**11**				(7)																				
	12				(7)																				
	13	5	5	5	(7)						13		5	5											
Online/electronic object based communication	**14**		7														(17)								
	15										13		13				(17)								
	16	6					11																		
	17		8														(17)								
	18											14					(17)								

Adapted from Sacks et al. (2010)

hypothetical interactions mostly on design related activities but also during construction processes, as presented on Tables 7 and 8, in which these new information technologies and production systems interactions enable much more complex and better sustainable development of constructions, a fact that has recently been drawing attention from government and society because reports have shown this industry as the most environmentally destructive one.

5.1. Theoretical implications

For academics, this research aims to contribute to the scientific community on the theme studied, since it presents a representative selection of international research in interdisciplinary area as it is a relevant issue in which there is a dialogue of sustainability science, business management and industrial engineering, enabling the researchers to contribute with relevant research. This paper makes multiple contributions to the body of BIM, lean and sustainability. In the existing literature, there are no studies that simultaneously investigate the current state-of-the-art of BIM, lean and green towards sustainable development and evaluate the importance of the integration of their technologies, methods and knowledges to construction sustainability, considering simultaneously the economic, environmental and social dimensions. Thus, this is the first attempt to systematically review the three themes with a reasonable amount of articles found. This way, the paper has fulfilled the gap in the literature by proposing interactions and a matrix that work as guidelines for better integration and performance of BIM-lean-green in construction projects, given a glimpse of the current situation of their main interactions and indicating fertile areas for further academic inquiry.

Furthermore, many issues are addressed which have not been covered properly in the past such as synergies and barriers, benefits and challenges of this integration. It is hoped that the study will inspire further research and exploration in this area. Our research also reveals interesting future research implications for the sustainability of AEC and the descriptive analysis illustrates an evolving research field with increasing consideration in academic journals especially in the last decade.

5.2. Practical implications

The result of this research offers some practical implications for professionals who want to continuously improve the sustainable performance of their organizations. For practitioners in this industry, the results of our systematic review represent a beneficial knowledge base and may be helpful in identifying various approaches to further improve both their productivity, and sustainability. Additionally, this study presents an integrative matrix that could be applicable as a guideline for the AEC industry in various contexts. Therefore, industry professionals can identify good opportunities in BIM-lean-green integration, not only in relation to improving excellence but also to pursue more socio-environmentally responsible practices.

From the managerial point of view, it is expected that there will be greater investment in information technologies, in the development and training of employees from multidisciplinary teams, in stimulating leadership, in aligning resources and in systematically managing the supply chain, in order to add value to construction projects and organizations. Furthermore, it is essential to focus their efforts on implementing proactive solutions, innovative methods and tools and real-time systems to collect accurate data, in order to calculate reliable sustainability measures.

5.3. Political implications

It is the responsibility of governments to dictate the rules, to define standards and to communicate them through strategic guidelines among the different stakeholders in the construction industry, with fundamental public transparency and economic incentives for the private sector in order to foster the sustainable development of the construction sector.

Thus, standards should clearly define the benchmarks for private and public building sectors, being necessary a carbon standard calculation at a government level for prefabricated buildings to reduce construction waste and to ease the adverse environmental effects (Ji et al., 2016). In addition, it is also essential to achieve a greater maturity of tools and techniques with top-down policies aimed at achieving the reduction of CO_2 emissions through the use of BIM in the operational phase of buildings (Peng, 2016) and from the collection of environmental taxes and charges.

Moreover, as stated by Caiado et al. (2017), we believe that the environmental policy could directly pressure organizations to search for sustainable actions; and the environmental logistics policy (e.g. environmental transportation, packaging, warehousing, and reverse logistics) could generate more transparency of information between stakeholders in the chain and the delivery of outputs with less environmental impact in their life cycle (eco-efficiency). Finally, governments may find the SLR results interesting, especially the proposed matrix, as they have the major roles in terms of investment, training, legislation and management, planning, operationalizing and controlling the sustainable performance.

5.4. Limitations and suggestion for future research

Finally, the study's limitations and suggestions for future studies are presented. Firstly, there is a restriction on the chosen databases that are constantly updated. There is also a temporal limitation, since the data were collected on a certain date, and there was a restriction on the choice of the keywords that guided the searches. In addition, this research focused on peer-reviewed articles and conference proceedings in English, disregarding documents in other languages and other sources of publication as books. Lastly, although the review followed a detailed and structured research process, the analysis of the adherence and alignment of the articles to the themes and consequent decision of the selected articles was also based on the evaluation of the researchers.

As a sequence to this work, further research should focus on improving and exploring the interrelationships to look for practical evidences and incrementally validate the framework. How this integration of BIM, lean and green paradigm should be executed for sustainable development of AEC requires deeper exploration. An analysis of certain interactions strongly encourages implementation of an indicator based (e.g. Life Cycle Cost (LCC), Life Cycle CO_2 emissions (LCCE), etc) system to support design decision making through analyses of multiple design alternatives and automatic extraction of model data for sustainable assessments, focusing on the conceptual stage as idealized by lean principles and required for sustainable project developments. Such system should be expansible to accommodate incremental addition of indicators and support user input of weightings to consider what the client values most (e.g. higher weight to LCC than LCCE if the user is more concerned with costs than environmental impact). It could also support multiple stakeholder weightings inputs to enable decision by participant consensus, considering all options. It is especially important to consider LCC because a lack of economic aspects could be perceived within articles in this review. Future researches should also consider social aspects coupled with the use of these tools and techniques in order to direct progress towards the sustainable development (Caiado et al., 2017).

Appendix A

Table A.9
BIM functionalities.

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

Adapted from Sacks et al. (2010).

Table A.10
Lean principles.

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

Adapted from Sacks et al. (2010).

References

Ahuja, R., Sawhney, A., Arif, M., 2017. Driving lean and green project outcomes using bim: a qualitative comparative analysis. Int. J. Sustain. Built Environ. 6, 69–80. https://doi.org/10.1016/j.ijsbe.2016.10.006.

Alwan, Z., Greenwood, D., Gledson, B., 2015. Rapid LEED evaluation performed with BIM based sustainability analysis on a virtual construction project. Constr. Innov. 15, 134–150. https://doi.org/10.1108/CI-01-2014-0002.

Alwan, Z., Jones, P., Holgate, P., 2017. Strategic sustainable development in the UK construction industry, through the framework for strategic sustainable development, using building information modelling. J. Clean. Prod. 140, 349–358. https://doi.org/10.1016/j.jclepro.2015.12.085.

Amado, M., Poggi, F., 2014. Solar urban planning: a parametric approach. Energy Proc. 48, 1539–1548. https://doi.org/10.1016/j.egypro.2014.02.174.

Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C., OReilly, K., 2011. Technology adoption in the bim implementation for lean architectural practice. Autom. Constr. 20, 189–195. https://doi.org/10.1016/j.ijsbe.2016.10.006.

Azhar, S., Brown, J.W., Sattineni, A., 2010. A case study of building performance analyses using building information modeling. In: 27th International Symposium on Automation and Robotics in Construction (ISARC 2010), pp. 213–222.

Azhar, S., Carlton, W.A., Olsen, D., Ahmad, I., 2011. Building information modeling for sustainable design and LEED ® rating analysis. Autom. Constr. 20, 217–224. https://doi.org/10.1016/j.autcon.2010.09.019.

Bae, J.W.W., Kim, Y.W.W., 2007. Sustainable value on construction project and application of lean construction methods. In: Lean Construction: a New Paradigm for Managing Capital Projects - 15th IGLC Conference. the International Group for Lean Construction, pp. 312–321.

Behzad, P., Sheryl, S.F., Prasad, N.M., 2015. A conceptual approach to track design changes within a multi-disciplinary building information modeling environment. Can. J. Civ. Eng. 42, 139–152. https://doi.org/10.1139/cjce-2014-0078.

BIM Task Group, 2013. 2-Construction 2025. Industrial Strategy: Government and industry in partnership.

Biswas, T., Krishnamurti, R., 2012. Data sharing for sustainable building assessment. Int. J. Archit. Comput. 10, 555–574. https://doi.org/10.1260/1478-0771.10.4.555.

Briner, R., Denyer, D., 2012. Systematic review and evidence synthesis as a practice and scholarship tool. In: Handbook of Evidence-based Management: Companies, Classrooms and Research.

Bryde, D., Broquetas, M., Volm, J., 2013. The project benefits of building information modelling (bim). Int. J. Proj. Manag. 31, 971–980. https://doi.org/10.1016/j.ijproman.2012.12.001.

Caiado, R., Dias, R.d.F., Mattos, L., Quelhas, O., Leal Filho, W., 2017. Towards sustainable development through the perspective of eco-efficiency - a systematic literature review. J. Clean. Prod. 165, 890–904. https://doi.org/10.1016/j.jclepro.2017.07.166.

Caldera, H., Desha, C., Dawes, L., 2017. Exploring the role of lean thinking in sustainable business practice: a systematic literature review. J. Clean. Prod. 167, 1546–1565. https://doi.org/10.1016/j.jclepro.2017.05.126.

Carneiro, S.B.M., Campos, I.B., De Oliveira, D.M., Neto, J., 2012. LEAN and green: a relationship matrix. In: IGLC 2012-20th Conference of the International Group for Lean Construction. The International Group for Lean Construction.

Chen, L., Luo, H., 2014. A BIM-based construction quality management model and its applications. Autom. Constr. 46, 64–73. https://doi.org/10.1016/j.autcon.2014.05.009.

Clemente, J., Cachadinha, N., 2013. BIM-lean synergies in the management on MEP works in public facilities of intensive use - a case study. In: 21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013. The International Group for Lean Construction, pp. 70–79.

Comm, C.L., Mathaisel, D.F.X., 2005. An exploratory analysis in applying lean manufacturing to a labor intensive industry in China. Asia Pac. J. Mark. Logist. 17, 63–80. https://doi.org/10.1108/13555850510672430.

Dadhich, P., Genovese, A., Kumar, N., Acquaye, A., 2015. Developing sustainable supply chains in the UK construction industry: a case study. Autom. Constr. 164, 271–284. https://doi.org/10.1016/j.ijpe.2014.12.012.

Dantas Gabriele, P., Tavares Treinta, F., Rodrigues de Farias Filho, J., Regina Brantes, S., 2012. Sustentabilidade e vantagem competitiva estratégica: um estudo exploratório e bibliométrico. Produção Online 12, 729–755. https://doi.org/10.14488/1676-1901.v12i3.975.

Dave, B., Boddy, S., Koskela, L., 2011. Visilean: designing a production management system with lean and BIM. In: 19th Annual Conference of the International Group for Lean Construction 2011, IGLC 2011. The International Group for Lean Construction, pp. 477–487.

Denyer, D., Tranfield, D., 2009. Chapter 39: Producing a Systematic Review. Sage Publications Ltd.

Dues, C.M., Tan, K.H., Lim, M., 2013. Green as the new Lean: how to use Lean practices as a catalyst to greening your supply chain. J. Clean. Prod. 40, 93–100. https://doi.org/10.1016/j.jclepro.2011.12.023.

Eastman, C., Teicholz, P., Sacks, R., Liston, K., 2011. BIM Handbook: a Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, vol. 2. https://doi.org/10.1002/9780470261309 arXiv:9809069v1.

Fercoq, A., Lamouri, S., Carbone, V., 2016. Lean/green integration focused on waste reduction techniques. J. Clean. Prod. 137, 567–578. https://doi.org/10.1016/j.jclepro.2016.07.107.

Garza-Reyes, J.A., 2015. Lean and green-a systematic review of the state of the art literature. J. Clean. Prod. 102, 18–29. https://doi.org/10.1016/j.jclepro.2015.04.064.

Gerber, D.J., Becerik-Gerber, B., Kunz, A., 2010. Building information modeling and lean construction: technology, methodology and advances from practice. In: Challenging Lean Construction Thinking: what Do We Think and what Do We Know? - 18th Annual Conference of the International Group for Lean Construction, IGLC 18. The International Group for Lean Construction, pp. 683–693.

Hallinger, P., 2013. A conceptual framework for systematic reviews of research in educational leadership and management. J. Educ. Adm. 51, 126–149. https://doi.org/10.1108/09578231311304670.

Hamdi, O., Leite, F., 2012. BIM and Lean interactions from the bim capability maturity model perspective: a case study. In: IGLC 2012-20th Conference of the International Group for Lean Construction. The International Group for Lean Construction.

Inyim, P., Rivera, J., Zhu, Y., 2014. Integration of building information modeling and economic and environmental impact analysis to support sustainable building design. J. Manag. Eng. 31 https://doi.org/10.1061/(ASCE)ME.1943-5479.0000308.

Jalaei, F., Jrade, A., 2015. Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings. Sustain. Cities Soc. 18, 95–107. https://doi.org/10.1016/j.scs.2015.06.007.

Ji, Y., Li, K., Liu, G., Shrestha, A., Jing, J., 2016. Comparing greenhouse gas emissions of precast in-situ and conventional construction methods. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.07.143.

Jrade, A., Jalaei, F., 2013. Integrating building information modelling with sustainability to design building projects at the conceptual stage. Build. Simul. 6, 429–444.

Khemlani, L., 2009. Sutter Medical Center Castro Valley: Case Study of an IPD Project AECBytes available at: http://www.aecbytes.com/buildingthefuture/2009/Sutter_IPDCaseStudy.html.

Khoshanava, S., Rostami, R., Rostami, R., Kiani, I., 2013. Application of softwares in green and sustainable construction - a case study in Malaysia. Asian J. Microbiol. Biotechnol. Environ. Sci. 15, 425432. https://doi.org/10.1016/j.jclepro.2016.12.010.

Koranda, C., Chong, W.K., Kim, C.C., Chou, J.S.S., Kim, C.C., 2012. An investigation of the applicability of sustainability and lean concepts to small construction projects. KSCE J. Civ. Eng. 16, 699–707. https://doi.org/10.1007/s12205-012-1460-5.

Kurdve, M., Shahbazi, S., Wendin, M., Bengtsson, C., Wiktorsson, M., 2015. Waste flow mapping to improve sustainability of waste management: a case study approach. J. Clean. Prod. 98, 304–315. https://doi.org/10.1016/j.jclepro.2014.06.076.

Lapinski, A.R., Horman, M.J., Riley, D.R., 2006. Lean processes for sustainable project delivery. J. Constr. Eng. Manag. 132 (10), 1083–1091. https://doi.org/10.1061/(ASCE)0733-9364.

Len, H., Calvo-Amodio, J., 2017. Towards lean for sustainability: understanding the interrelationships between lean and sustainability from a systems thinking perspective. J. Clean. Prod. 142, 4384–4402. https://doi.org/10.1016/j.jclepro.2016.11.132.

Li, B., Fu, F.F., Zhong, H., Luo, H.B., 2012. Research on the computational model for carbon emissions in building construction stage based on BIM. Struct. Surv. 30, 411–425. https://doi.org/10.1108/02630801211288198.

Liu, S., Meng, X., Tam, C., 2015. Building information modeling based building design optimization for sustainability. Energy Build. 105, 139–153. https://doi.org/10.1016/j.enbuild.2015.06.037.

Marzouk, M., Othman, A., 2017. Modeling the performance of sustainable sanitation systems using building information modeling. J. Clean. Prod. 141, 1400–1410. https://doi.org/10.1016/j.jclepro.2016.09.226.

de Medeiros, J.F., Ribeiro, J.L.D., Cortimiglia, M.N., 2014. Success factors for environmentally sustainable product innovation: a systematic literature review. J. Clean. Prod. 65, 76–86. https://doi.org/10.1016/j.jclepro.2013.08.035.

Motawa, I., Carter, K., 2013. Sustainable bim-based evaluation of buildings. Proc. - Soc. Behav. Sci. 74, 419–428. https://doi.org/10.1016/j.sbspro.2013.03.015.

Nguyen, T.H., Shehab, T., Gao, Z., 2010. Evaluating sustainability of architectural designs using building information modeling. Open Constr. Build. Technol. J. 4, 1–8. https://doi.org/10.2174/1874836801004010001.

Novak, V.M., 2012. Value paradigm: revealing synergy between lean and sustainability. In: IGLC 2012-20th Conference of the International Group for Lean Construction. The International Group for Lean Construction.

Ogunbiyi, O., Oladapo, A., Goulding, J., 2013. An empirical study of the impact of lean construction techniques on sustainable construction in the UK. Constr. Innov. 14, 88–107. https://doi.org/10.1108/CI-08-2012-0045.

Ortiz, O., Castells, F., Sonnemann, G., 2009. Sustainability in the construction industry: a review of recent developments based on lca. Constr. Build. Mater. 23, 28–39. https://doi.org/10.1016/j.conbuildmat.2007.11.012.

Oskouie, P., Gerber, D.J., Alves, T., Becerik-Gerber, B., 2012. Extending the interaction of building information modeling and lean construction. In: IGLC 2012-20th Conference of the International Group for Lean Construction. The International Group for Lean Construction.

Oti, A.H., Tizani, W., 2015. BIM extension for the sustainability appraisal of conceptual steel design. Adv. Eng. Inf. 29, 28–46. https://doi.org/10.1016/j.aei.2014.09.001.

Peng, C., 2016. Calculation of a building's life cycle carbon emissions based on ecotect and building information modeling. J. Clean. Prod. 112, 453–465. https://doi.org/10.1016/j.jclepro.2015.08.078.

Piercy, N., Rich, N., 2015. The relationship between lean operations and sustainable operations. Int. J. Oper. Prod. Manag. 35, 282–315. https://doi.org/10.1108/

IJOPM-03-2014-0143.
Reim, W., Parida, V., Ortqvist, D., 2015. Product-Service Systems (PSS) business models and tactics - a systematic literature review. J. Clean. Prod. 97, 61–75. https://doi.org/10.1016/j.jclepro.2014.07.003.
Rischmoller, L., Alarcón, L., Koskela, L., 2006. Improving value generation in the design process of industrial projects using cavt. J. Manag. Eng. 22 (2), 52–60. https://doi.org/10.1061/(ASCE)0742-597X.
Rosenbaum, S., Toledo, M., Gonzalez, V., 2012. Green-lean approach for assessing environmental and production waste in construction. In: IGLC 2012-20th Conference of the International Group for Lean Construction. The International Group for Lean Construction.
Rosenbaum, S., Toledo, M., Gonzalez, V., 2014. Improving environmental and production performance in construction projects using value-stream mapping: case study. J. Constr. Eng. Manag. 140 https://doi.org/10.1061/(ASCE)CO.1943-7862.0000793.
Sacks, R., Koskela, L., Dave, B.A., Owen, R., 2010. Interaction of lean and building information modeling in construction. J. Constr. Eng. Manag. 136, 968–980. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000203.
Sacks, R., Treckmann, M., Rozenfeld, O., 2009. Visualization of work flow to support lean construction. J. Constr. Eng. Manag. 135, 1307–1315. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000102.
Salehi, Yaghtin, 2015. Action research innovation cycle: lean thinking as a transformational system. In: 3rd International Conference on Leadership, Technology and Innovation Management. Procedia - Social and Behavioral Sciences, pp. 293–302.
Salgueiro, I.B., Ferries, B., 2015. An "environmental BIM" approach for the architectural schematic design stage. Int. J. Archit. Comput. 13, 299–312.
Saunders, M., Lewis, P., Thornhill, A., 2012. Research Methods for Business Students. Pearson Education Limited.
Siddaway, A., 2014. What Is a Systematic Literature Review and How Do I Do One?.
Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2007. Development of composite sustainability performance index for steel industry. Ecol. Indic. 7, 565–588. https://doi.org/10.1016/j.ecolind.2006.06.004.
Valente, C.P., Mourao, C.A.M., De Neto, J.P.B., 2013. Lean and green: how both philosophies can interact on strategic, tactical and operational levels of a company. In: 21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013. The International Group for Lean Construction, pp. 885–894.
Viegas, C.V., Bond, A., Vaz, C., Borchardt, M., Pereira, G., Selig, P., Varvakis, G., 2016. Critical attributes of sustainability in higher education: a categorisation from literature review. J. Clean. Prod. 126, 260–276. https://doi.org/10.1016/j.jclepro.2016.02.106.
Webster, J., Watson, R.T., 2002. Analyzing the past to prepare the future: writing a literature review. MIS Q. 25, 13–26.
Wong, J.K.W., Kuan, K.L., 2014. Implementing 'BEAM Plus' for BIM-based sustainability analysis. Autom. Constr. 44, 163–175. https://doi.org/10.1016/j.autcon.2014.04.003.
Wong, W.P., Wong, K.Y., 2014. Synergizing an ecosphere of lean for sustainable operations. J. Clean. Prod. 85, 51–66.