Pontifícia Universidade Católica
do Rio de Janeiro

Pedro Saieg Faria

Evaluating the Interplay between BIM, Lean and Sustainability Concepts in Building Design

Dissertação de Mestrado

Dissertation presented to the Programa de Pós-graduação em Engenharia Civil of PUC-Rio as partial fulfillment of the requirements for the degree of Mestre em Engenharia Civil.

Advisor: Profa. Elisa Dominguez Sotelino

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I dedicate this work to my family, who has always supported me and fought to make sure I could accomplish this moment.

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To my mother and father, without whom nothing I have done so far would have been possible. There are no words that could describe all you have done to make sure I would get where I am, that I would have the opportunities I had. My victories are dedicated to you.

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Abstract

Faria, Pedro Saieg; Sotelino, Elisa Dominguez (Advisor). **Evaluating the Interplay between BIM, Lean and Sustainability Concepts in Building Design**. Rio de Janeiro, 2017. 102p. Dissertação de Mestrado – Departamento de Engenharia Civil, Pontifícia Universidade Católica do Rio de Janeiro.

The main purpose of this study was to evaluate and validate how Building Information Modeling functionalities could interact with lean construction principles to support sustainable development in building design and deliver higher quality projects. To that end, first a brief introduction to each of these concepts was introduced, followed by an extensive and structured literature research looking for pairwise combination of these topics. The results of this review generated a matrix that brought up interactions, which were highlighted and explained. To further validate some of these interrelationships, a plug-in was proposed and implemented on a BIM enabled visualization environment to help the user decide the best design between alternatives, while considering his perspective on what generates value to the project. To illustrate and validate the usability and importance of the plug-in, the design of a warehouse with certain requirements was considered. Four design alternatives were modelled considering different types of superstructures along with the building envelope and varied types of materials. These models were exported as IFC files and then imported to the BIM environment. The plug-in then imported an external database and calculated general costs, CO_2 emissions and thermal comfort indicators for each model based on data contained on elements and the imported database. Finally, it considered user weightings on each indicator and graphically displayed results indicating which of the options would be the best through a Multiple Attribute Decision Method. Even though the used models were hypothetical and more indicators would be required for more robust results, it was possible to verify that automated analysis considering indicators can optimize decision making tasks that otherwise would be inefficient and innacurate. This way, some of the perceived interactions were validated and the importance of integrating these concepts was confirmed.

Keywords

BIM; sustainability; lean thinking; design performance; BIM plug-in.

Resumo

Faria, Pedro Saieg; Sotelino, Elisa Dominguez. **Avaliação do Inter-relacionamento entre os Conceitos BIM, Lean e Sustentabilidade em Projetos de Edificações.** Rio de Janeiro, 2017. 102p. Dissertação de Mestrado – Departamento de Engenharia Civil, Pontifícia Universidade Católica do Rio de Janeiro.

O principal objetivo deste estudo foi avaliar e validar como funcionalidades da Modelagem da Informação da Construção (BIM) podem interagir com princípios da construção enxuta para contribuir para o desenvolvimento sustentável em projetos de construção e alcançar projetos de maior qualidade. Para este fim, primeiramente uma breve revisão de cada um destes conceitos foi introduzida, seguida por uma extensiva e estruturada revisão da literatura, buscando combinações par a par destes tópicos. Os resultados desta revisão deram origem à uma matriz que que consolidou as interrelações, que foram destacadas e explicadas. Para validar algumas destas interrelações, um plug-in foi proposto e implementado em um ambiente de visualização BIM para ajudar o usuário a decidir pelo melhor projeto dentre diferentes alternativas, considerando também a perspectiva do usuário em termos do que mais gera valor ao projeto. Para ilustrar e validar a usabilidade e importância do plug-in, o projeto de um galpão com determinados requerimentos foi considerado. Quatro alternativas de projeto foram modeladas considerando diferentes tipos de superestrutura e envelope das edificações, bem como variados materiais. Estes modelos foram exportados como arquivos IFC e então importados no ambiente BIM. Através do plug-in desenvolvido, foi então importada uma base de dados externa e calculados os indicadores de custos gerais, emissões de CO_2 e comforto térmico para cada modelo baseados nos dados contidos nos elementos e na base de dados importada. Finalmente, foram consideradas ponderações inseridas por usuários para cada indicador e exibidos os resultados em forma de gráficos, indicando a melhor opção através de um Método de Decisão de Múltiplos Atributos. Apesar de os modelos utilizados nesta pesquisa terem sido hipotéticos e mais indicadores serem necessários para melhores resultados, foi possível verificar que análises automatizadas podem otimizar tarefas de tomada de decisão que em outras circunstâncias seriam ineficientes e imprecisas. Desta forma, algumas das interações percebidas foram validadas e a importância da integração

entre os conceitos foi confirmada.

Palavras-chave

BIM; sustentabilidade; pensamento enxuto; desempenho de projetos; extensão BIM.

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List of abbreviations

BIM	Building Information Modelling
MADM	Multi Attribute Decision Method
SLR	Systematic Literature Review
AEC	Architecture Engineering and Construction
LEED	Leadership in Energy and Environmental Design
MEP	Mechanical Electrical and Plumbing
LPS	Las Planner System
VSM	Value Stream Mapping
CAVT	Computer Aided Visualization Tool
GIS	Geographical Information System
LCA	Life Cycle Analysis
BOM	Bill of Material
PSO	Particle Swarm Optimization
LCC	Life Cycle Cost
LCCE	Life Cycle Carbon Emission
POE	Post-Occupancy Evaluation
API	Application Programming Interface
BREEAM	BRE Environmental Assessment Method
ICT	Information and Communication Technology
CAD	Computer Aided Design
LOD	Level of Development
IFC	Industry Foundation Classes
WFM	Waste Flow Mapping
KPI	Key Performance Indicator
IPD	Integrated Project Delivery
DB	Design-Build
JIT	Just in Time
TBL	Triple Bottom Line
ULS	Ultimate Limit State
SLS	Service Limit State
ICE	Inventory of Carbon and Energy

List of symbols

DE_C	Design cost of the category
MA_C	Material acquisition cost of the category
RA_p	Cost of the material design
V_e	Volume of the element
V	Volume of the category
MT_C	Cost of the material design
A_e	Area of the element
MT_{cv}	Material cost per volume
MT_{cw}	Material cost per weight
SL_F	Site loss factor
MT_d	Density of the material
MT_{ca}	Material cost per area
MT_{cu}	Material cost per unit
MT_q	Material quantity
CA_c	Construction Activities cost
NR_{iuv}	Number of input units required for activity per volume
IP_{cv}	Cost of input unit per volume
NR_{iuw}	Number of input units required for activity per weight
IP_{cw}	Cost of input unit per weight
DM_c	Demolition cost
DE_{cv}	Demolition cost of the material per volume
DE_{cw}	Demolition cost of the material per weight
EP_{CO2}	Emission of CO_2 gases on the production process
EF_m	Emission factor of manufacturing
EF_r	Emission factor of chemical reactions
ET_{CO2}	Emission of CO_2 gases on the transportation process
TM_c	Transport modal consumption
FU_e	Fuel emission
DI_s	Distance from supplier to site
HF_w	Heat flow on walls
HF_R	Heat flow on roofs

T_{ext}	Exterior temperature
T_{int}	Interior temperature
ER_e	External resistance of the element
TT_e	Thermal transmittance of the material
Fac_r	Roof specific factor to consider atmosphere effects
AC_e	Absorptance of the element based on its material
SR_{eo}	Solar radiation based on element’s cardinal orientation
D_j	Desirability score for a particular alternative
n	Number of attributes
w_i	Weight of attribute
r_{ij}	Normalized score of the alternative on the criteria

The positive thinker sees the invisible, feels the intangible, and achieves the impossible.

Winston S. Churchill

1
Introduction

1.1
Motivation

The current recession Brazil is experiencing has direcly affected the construction industry, usually known for being one of the least productive and most wasteful sectors worldwide. According to Santos (2015) the industry is currently suffering its worst moment since 2003.

Despite the negative economic effects the scenario presents, it does bring to light the necessity of industry evolution in terms of work process methodology, development of new techniques and use of emerging technologies. Because according to Nguyen et al. (2010) the construction industry is the main villain of sustainable development among all sectors and due to the ever-increasing pressure from society and health organizations, sustainability became an especially important discussion matter within the industry.

1.2
Objective

In this context, this study aims to identify how Building Information Modeling (BIM), the most proeminent information technology for the construction industry, Lean Thinking principles of project and production efficiency and waste reduction along with Sustainable development aspects can be integrated to generate economicity and decrease environmental impacts, thus enabling more optimized and competitive solutions to address the current and future scenarios.

1.3
Methodology

To this end, this research seeks to understand how these three concepts can be integrated through a structured literature review. It was found that there has been no studies that clearly correlate them all together, even though pairwise combinations have been somehow investigated. By deeply studying and analyzing goals and findings of these pairwise concept combination research works, a framework was developed to aid future research on the subject. A BIM-based prototype system based on important indicators of cost efficiency and environmental impacts was implemented considering lean principles and further tested on hypothetical, but realistic examples to validate some of the perceived interrelationships.

1.4
Research Structure

The remainder of this document is structured as follows. Chapter 2 introduces a brief review of each of the concepts and their present applications and perspectives. It also presents the research methodology to identify current research that addresses the interrelationship aspects of the three studied areas, as well as goals and findings of the studies reviewed. Chapter 3 organizes the author’s perception on how integration of the fields can occur and defines the prototype system idea based on the described framework. Then, it presents choices of structural and architectural design aspects of hypothetical examples, followed by geometry and data file transferring procedures. It ends by describing the metrics used to calculate indicators and how the system supports the decision making process, while also describing the computational implementation undertaken. Finally, Chapter 4 discusses results of the implemented methodology application on the described example and Chapter 5 presents conclusions and future research recommendations.

2
Structured Literature Review and Analysis

2.1
Brief Review of Concepts

2.1.1
Building Information Modelling

The BIM Academy (2013) defines Building Information Modelling as a process involving the structured creation, sharing, use and re-use of digital information about a building or built asset throughout its entire life cycle, from design through procurement, construction and beyond into its operation and management. This involves the use of coordinated 3D design models enriched with data, which are created and managed using a range of interoperable technologies.

This process describes the means by anyone could an enterprise through the use of a digital model which draws from a range of data assembled collaboratively. Creating a digital Building Information Model (BIM) enables those who interact with the enterprise to optimize their actions, resulting in a greater entire life value of the asset (Waterhouse & Philp, 2016).

According to Succar (2009), BIM is an emerging significant technological and procedural shift within the Architecture, Engineering, Construction and Operations (AECO) industry. Because this industry is known for being one of the most traditional ones in terms of work processes, BIM imposes significant challenges for adoption, despite the clear benefits the methodology introduces.

From a practical standpoint, the use of BIM can bring significant technological advantages compared with conventional methods of producing and handling project information (Alwan, et al., 2015). Consequently, it makes the process more efficient and cohesive through team collaboration. Also, more reliable planning and scheduling are possible, because it diminishes conflicts and errors that would otherwise only be noticed at the time of construction.

Figure 1: Comparison of BIM against traditional design processes effort curves is a well-known BIM chart that represents the paradigm shift of BIM adoption from

traditional construction methods. It depicts the effort curve being drawn to the beginning of the timeline, where changes have considerably less impacts on costs and schedules.

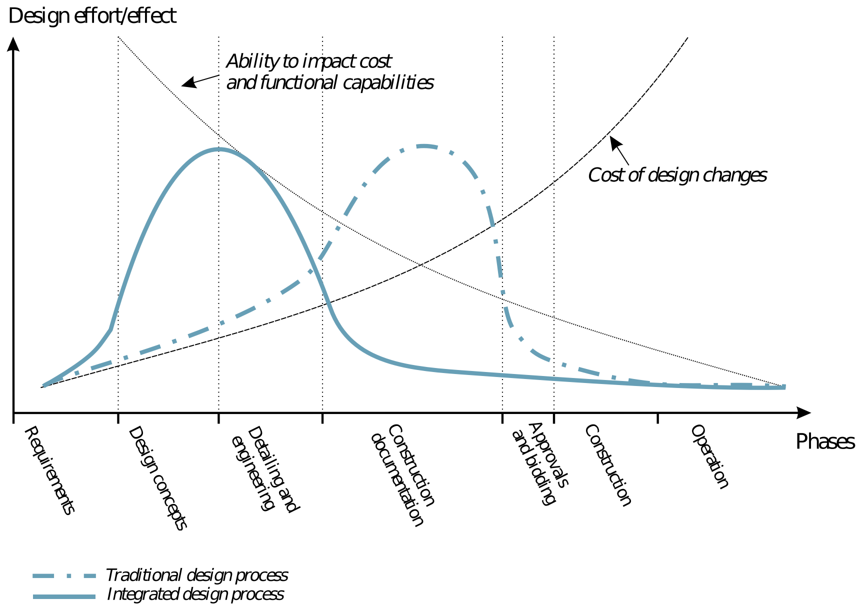

Figure 1: Comparison of BIM against traditional design processes effort curves

Source: MacLeamy (2011)

One of the most important aspects of the centralized and up-to-date model is the capability of storing element data, which provides intelligence and the possibility of iterative and automated analysis. In the tradional methodology this would be a manual, time consuming and inefficient procedure.

Since there is no single tool capable of dealing with all phases and requirements of a building development process, tools need to have the ability to communicate with each other, ensuring reliable information transfers. This ability is called interoperability, and is a challenge brought by this new realm enabled by BIM processes. It is, currently, an important BIM adoption barrier that has been continually improved, but has not yet been completely addressed.

The most proeminent solution to overcome this challenge is the Industry Foundation Classes (IFC) Schema (Froese, 2002), a formal specification used to represent the structure of information and how that information relates to other information. It was developed by BuildingSMART and is used to describe building and construction industry geometry and attribute data. For this interoperability to work, the only requirement is that softwares are able to import and export IFC based models, thus discarding the need for software companies to create specific solutions to read files from each other (point to point).

2.1.2
Lean Construction

Lean construction (LC) is the term used to define the application of lean thinking principles to the construction environment. It is a conceptual approach to project and construction management and refers to the application and adaptation of the underlying concepts and principles of the Toyota Production System (TPS) to construction, which are described later on. As in the TPS, the focus of lean construction is on reduction of waste, increase of value to the customer, and continuous improvement. While many of the principles and tools of the TPS are applicable as such in construction, there are also principles and tools in lean construction that are different from those of the TPS (Sacks, et al, 2010).

According to the Lean Construction Institute, LC is a continuous process that is applied through design, procurement, manufacturing and construction. It is an integrated process in which clients, designers, contractors, and suppliers must be committed to working together, focussing on delivering value (as seen by the ultimate customer) rather than low cost, and striving to get it ‘right first time’.

From the design perspective, lean construction explores the fact that the influence of the design phase on the outcome of any project, either technically or economically, is immense. It is in the design phase that the customer’s ideas and speculations are conceptualized into a physical model, and the customer’s needs and requirements are defined into procedures, drawings and technical specifications.

According to Tzortzopoulos and Formoso (1999), the traditional design process fails to minimize the effects of complexity and uncertainty, to ensure that the information available to complete design tasks is sufficient, and to reduce inconsistencies within construction documents. Lean design is introduced as a way of reducing waste, unnecessary uncertainty, and improving value generation as early as in the design phase.

2.1.3 Sustainable Construction

The LafargeHolcim Foundation (2015) states that in the construction world, buildings have the capacity to make a major contribution to a more sustainable future for our planet. The Organisation for Economic Co-operation and Development (OECD) (2002), for instance, estimates that buildings in developed countries account for more than forty percent of energy consumption over their lifetime (incorporating raw material production, construction, operation, maintenance and decommissioning). Added to this, the fact that over half of the world's population live in urban environments, then it becomes clear that sustainable buildings have become vital cornerstones to ensure long-term environmental, economic and social viability.

The sustainable building process minimizes the environmental impact of construction from site development to procurement and use of materials to the safe reuse, "deconstruction" or disposal of a building at the end of its useful life. In its widest sense, green building is about sustainability, which is defined by the Brundtland Comission (1987) as "the ability to provide for the needs of current generations without diminishing the capacity for future generations to do the same". According to Elkington (2004), green building should consider the Triple Bottom Line (TBL) of financial, social and environmental performance during the process.

Green design is about finding the balance between high-quality construction and low environmental impact. A lighter footprint means a longer-lasting planet, which is a positive aspect for the builder, client and environment. Viewing sustainable building as a process is important, because green-building success is not just a matter of building with green materials, but the combination of materials and processes to maximize efficiency, durability and savings.

There are a number of rating systems with defined metrics that encourage taking greener approaches during design and construction to generate less impact on the environment in exchange for certifications of resource efficiency. These have been gaining attention of the companies since society and the government are increasingly more concerned about environmental impacts on the planet. Amongst them, the Leadership in Energy and Environmental Design (LEED) Green Building Rating

System™ stands out (Alwan, et al. 2015). It was developed by the U.S. Green Building Council and is the primary certification used to measure and designate green buildings.

2.2
Literature Research Methodology

An extensive number of research works are conducted every year, sometimes reporting conflicting results. Targeting at reducing these conflicts, identifying gaps on the subject in the literature and to direct further research on the same subject, the concept of Systematic Literature Review (SLR) was developed.

This review was based on the principles of SLR, as 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, it was based on a strategy that aims to detect as much as possible of the relevant literature. By documenting the strategy of the research, it allows the reader to assess its rigor as well as its completeness 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 has not been 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 & 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. This increases the likelihood of detecting real effects (e.g. realizing a certain consequence always happens after a certain action) that smaller studies are not capable of doing.

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

Following considerations of Denyer & Tranfield (2009), Garza-Reyes (2015) and de Medeiros, Ribeiro & Cortimiglia (2014), 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 Figure 2 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.

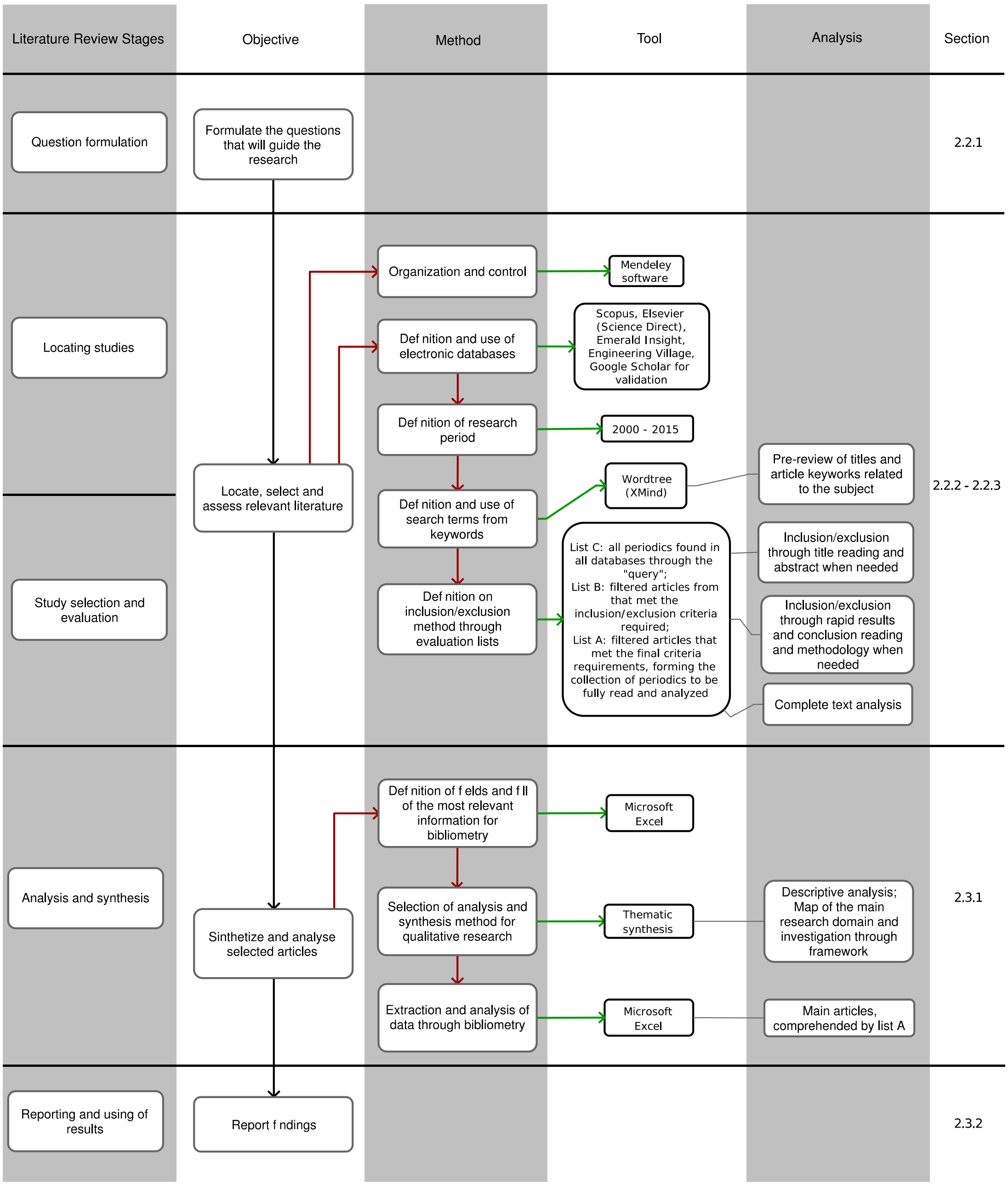

Figure 2: Framework of the research methodology undertaken

2.2.1
Question Formulation

The evolution of civil construction recently added 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?

2.2.2
Locating Studies

The search strings used to find the most relevant studies were based on the word-tree, concept of Dantas Gabriele et al. (2012). It was constructed by considering relevant terms found in the literature of the subjects of interest. According to Siddaway (2014), search strings operationalize research questions and help find the maximum amount of articles potentially relevant to 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 Figure 3.

The initial research string was defined using boolean operators “AND” and “OR” as specified in Table 1. However 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 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.

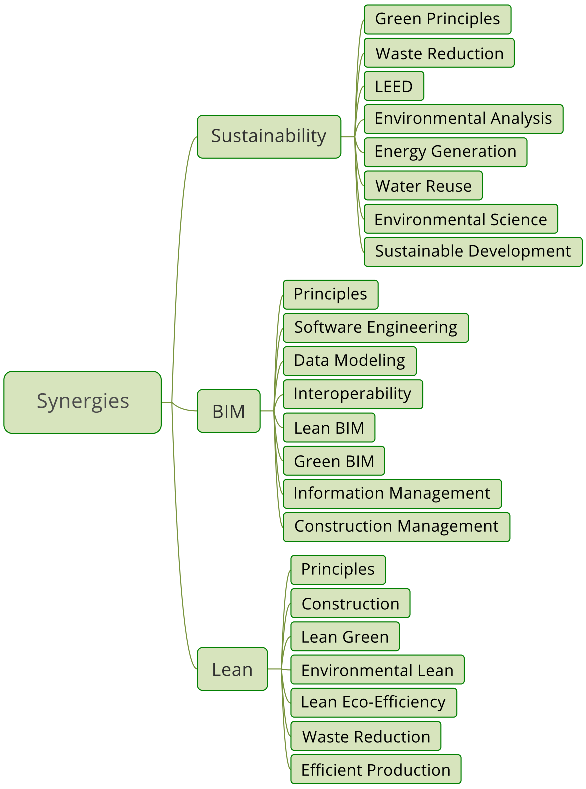

Figure 3: Word tree of search terms

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 ...)

2.2.3
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, the period between 2000 to 2016 was chosen because since the beginning of the millennium sustainability has become a major societal concern of and has since then received larger investments. Another reason is that it is also clear that the growth of publication in the subject has grown exponentially during this period. A few articles could not be considered because their full texts were not available.

Reim et al. (2015) affirm 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 established 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 summarizes 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. The latter were fully read and the information of interest was extracted providing a descriptive and thematic analysis.

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 the word environment but not in the sense of sustainability (e.g. work environment)
	Mentions the word sustainability but not as proposed by this research (e.g. sustainable economy)

2.3
Research Results and 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 2.3.1. Then, a descriptive analysis of main objectives of each authors's research works 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 2.3.2.1, 2.3.2.2 and 2.3.2.3 respectively. Section 3.1 presents the view of the author on how BIM and Lean can be integrated to achieve more sustainable developments in the AEC domain by adapting the interrelationship matrix developed by Sacks et al. (2010) and describing found interactions.

2.3.1
Quantitative

Figure 4a shows that even though publications are slightly scattered, there is a growing research tendency especially for BIM and sustainability topics, with slightly less attention being given to lean. It also shows 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.

Considering the location from where research works were published, and not the nationality of authors, Figure 4b 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 Figure 4c that even though the United States presents a bigger volume of published articles, it is in the United Kingdom that the rate of increase in articles was observed. This may be directly related to the BIM Task Group (2013) initiative, which demands BIM use for any government related project and also has the objective of reducing by 50% greenhouse gas emissions by 2025.

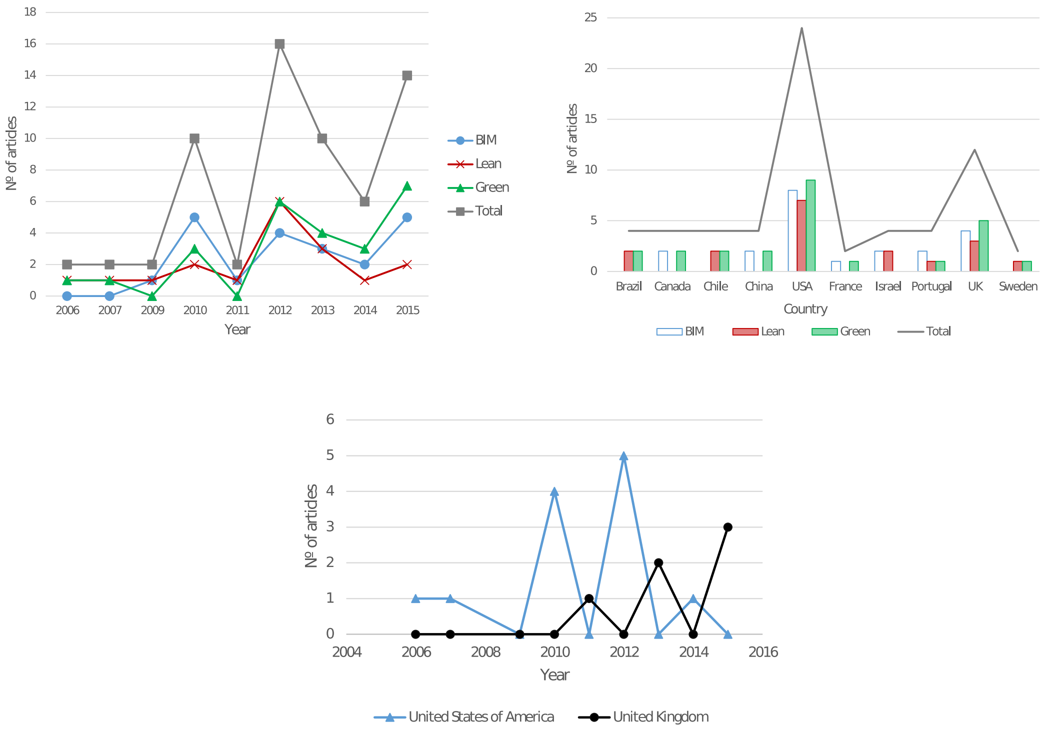

Figure 4: (a) articles per year for BIM, Green and Lean, (b) articles per country for BIM, Green and Lean, (c) total articles per year on the UK and USA

Table 3 presents the list of articles reviewed and their associated numbers to facilitate the understanding of the thematic synthesis depicted on Figure 5. The articles were subdivided according to their method, approach and by which of the 5Ds of sustainability are addressed (Economic, Environmental, Governance, Social and Technical), defined by Singh et al. (2007).

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 & 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 & Kim, 2007)	Sustainable value on construction project and application of lean construction methods
7	(Biswas & Krishnamurti, 2012)	Data sharing for sustainable building assessment
8	(Carneiro, et al., 2012)	LEAN and green: A relationship matrix
9	(Clemente & 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 & 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 & Jrade, 2015)	Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings
16	(Jrade & Jalaei, 2013)	Integrating building information modelling 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 & 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 & 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 & 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

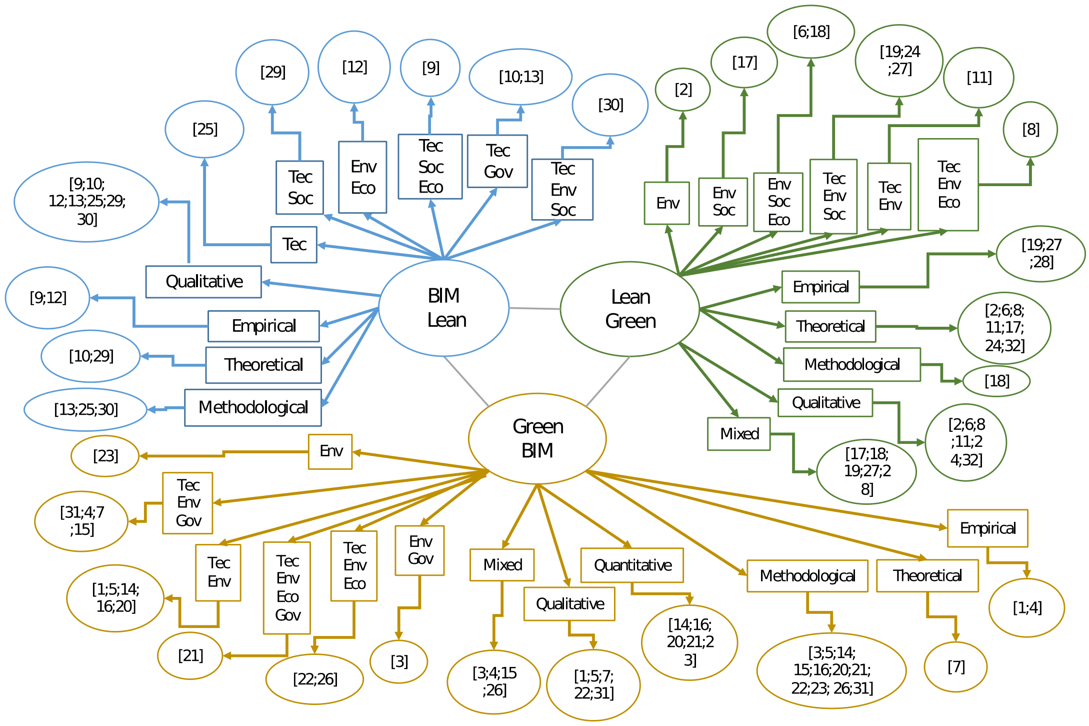

Figure 5: Thematic synthesis of the literature review

2.3.2
Descriptive

2.3.2.1
BIM and Lean

Hamdi and Leite (2012) identified relationship aspects of BIM and lean mainly focusing on the construction phase and from 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 the matrix of relationship previously developed by Sacks et al. (2010). 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. It allows the implementation of the Last Planner System (LPS) and provides better quality discussions based on 3D visualization, which 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) analyzed through a Value Stream Map (VSM) how activities are being conducted on a Mechanical, Electrical and Plumbing (MEP) renovation project. They identified tasks duration and value adding activities, and defined procedures based on lean principles. They also provided solutions through collaborative participation on two daily meetings to define which activities were finished and the next day's schedule based on the LPS and with the aid of a BIM model. The case study is used to associate lean principles to each implemented BIM functionality.

Oskouie et al. (2012) sought to expand Sacks et al.'s (2010) relationship matrix exploring and explaining new interactions and by proposing other functionalities and principles based on industry cases and academic projects especially during operation phase. They also identified whether these interactions had already been found in the literature. The researched lean principles included "Reduce Variability" and "Reduce Cycle Times", demonstrating a focus on efforts of prevention and scheduling. On the 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" were the most studied, evidencing an interest in technologies of "Real-Time Data Aquisition 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 used BIM model based visualization to implement lean construction methods and facilitate the understanding of construction processes transparently.

Sacks et al. (2010) rigorously examined interactions between lean principles and BIM functionalities through a relationship matrix to determine whether synergies exist or not and to serve as a conceptual framework for future research to explore the applications of each interrelationship. They also described 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.

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 explored the use of BIM and the synchronizing with scheduling software solutions and experts to reduce waste caused by poor coordination in order to maximize value for the entire project constituency by ensuring Look-Ahead collaboration.

Table 4 presents the main conclusions found by the authors extracted from the literature review as well as the respective references.

Table 4: BIM-lean findings from the literature

Findings	References
Most important feature of BIM is the structured, centralized, defined, easy access and exchangeable information, and not 3D modeling	(Hamdi & Leite, 2012), (Sacks, et al., 2009)
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)
Direct transfer of fabrication instructions to numerically-controlled machinery eliminates opportunities for human error in transcribing information	(Gerber, et al., 2010)
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)
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)
Reviewed studies were advancements because they delivered added value to the client and significantly reduced material, time and financial wastes	(Gerber, et al., 2010)
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 & Cachadinha, 2013), (Sacks, et al., 2009)
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)
BIM proved to be a great asset to facilitate lean construction practices	(Clemente & Cachadinha, 2013)
Conceptual analysis of BIM and lean construction indicates synergies from the design phase to delivery and operation	(Dave, et al., 2011)
Most lean construction principles have parallel functionalities in BIM methodology	(Clemente & Cachadinha, 2013)
Most efforts in the area tend to focus on the project and construction scheduling stages	(Sacks, et al., 2009)

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)
There is a growing interest in exploring BIM for facility management practices to minimize maintenance and expansion related costs	(Oskouie, et al., 2012)
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 & Cachadinha, 2013)
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)
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)
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)
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)
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)
One member of each team should be designated to update the model regularly since this demands time	(Clemente & Cachadinha, 2013)
Experience of stakeholders is key to optimize the use of BIM functionalities to serve lean practices	(Hamdi & Leite, 2012)
Selection of lean practices to be implemented in a project should be based on the company's 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 & Leite, 2012), (Sacks, et al., 2010)
Live links between the BIM platform and information management systems are fundamental	(Sacks, et al., 2009)
For comprehensive realization of the benefits BIM-lean integration can provide, a deep understand of the production theory is required	(Sacks, et al., 2010)
Interoperability between BIM software tools is still the greatest barrier for its full implementation	(Dave, et al., 2011)
The lack of capacitated professionals is a barrier for BIM implementation to support lean practices	(Dave, et al., 2011), (Clemente & Cachadinha, 2013)
High software/hardware initial investment requirement is one of BIM's main adoption barriers	(Clemente & Cachadinha, 2013)
It is difficult to estabilish a link with models that are stll undergoing modifications	(Dave, et al., 2011)
BIM can contribute but its adoption is not impediditive for lean construction implementation	(Novak, 2012)
Acceptance of yet another system to be used by workers may present a challenge for adoption	(Dave, et al., 2011)
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)
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)
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)
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)
Exponencial improvements of hardware and software are making the use of BIM in the field a reality	(Dave, et al., 2011)

2.3.2.2 BIM and Sustainability

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 that involved 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 and determine its potential of solar generation by subdividing it in delimited areas alluding to atoms, in which urban units behave as positive, negative or neutral regarding energy use. 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 on how the project's operation is performing compared with the predictions. They analyzed annual heating and cooling loads, use of natural gas and electricity, CO_2 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 through a literature review and data obtained from interviews of industry professionals. They aimed at displaying in which phase of the project documentation can be prepared and which LEED credits can be explored with the support of BIM tools. The validation was performed with an example using IES-VE software.

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

Inyim et al. (2014) evaluated and optimized a construction project through the development of a system, which was based on three criteria collectively: time, cost and environmental impact (CO_2 emissions). They take advantage of a multi-objective genetic algorithm to determine the possible combinations of previously selected components and materials to achieve the closest to optimal result. They concluded that the developed tool benefits the AEC industry by utilizing and extending BIM capacity during design and construction phases.

Jrade and Jalaei (2013) aimed at allowing designers to have a vision of how sustainable their project is, in real time, during the conceptual development stage. They conducted Life 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 research seeking to integrate a plug-in into a BIM tool. The extension estimated the “soft cost”, which considers costs of project, commissioning, documentation, energy modeling, certification and registry to obtain LEED (New Construction) certification. It also automated the process of identifying the number of required points based on the selection of LEED categories, suggesting the most adequate level of certification. Finally, they presented 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 decisions 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. It aims to fulfill a gap in tools to estimate CO_2 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. They 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. The algorithm then evaluates all combinations and 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 CO_2 Emissions (LCCE) is achieved.

Oti and Tizani (2015) created a modeling framework by developing a BIM based plug-in 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. Their article explains in detail the implementation process, the requirements and the 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 for 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 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 that five criteria can be automatically and five partly automatically obtained. They also described activities and information exchanges through a process map (adapted from Eastman et al. (2011)). Finally, they 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 from their research works. It also references where each finding can be encountered in the literature.

Table 5: BIM-green findings from the literature

Findings	References
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)
Previous research demonstrate the viability of semi-automated assessments with BIM tools	(Biswas & Krishnamurti, 2012)
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)
Evaluation of sustainable projects require information that is agregated 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 & Krishnamurti, 2012), (Motawa & Carter, 2013)
Inclusion of environmental impacts in the optimization process facilitates the integration of green construction concepts in traditional practices	(Inyim, et al., 2014)
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)
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 & Jalaei, 2013), (Jalaei & Jrade, 2015), (Liu, et al., 2015), (Salgueiro & Ferries, 2015)
The integration of BIM and sustainability principles has the potential of altering traditional practices to produce high performance projects	(Jalaei & Jrade, 2015)
BIM has Information and Communication Technologies (ICTs) that allow the various stakeholders to collaborate during the whole lifecycle of a building	(Motawa & Carter, 2013)
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 & Carter, 2013)
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)
The development of Green BIM tools which integrates the design model and the simulation can analyse multi-disciplinary information in a single model which improves the analysis and eliminates errors of data handling	(Azhar, et al., 2011)
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)
To achieve CO_2 goals, better performance monitoring and information sharing are required from the moment the project is delivered, and BIM provides the necessary technology	(Motawa & Carter, 2013)
Stakeholder integration and collaboration is essential for the development of sustainable projects and BIM eases this complex process	(Biswas & Krishnamurti, 2012), (Alwan, et al., 2015)
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 & Ferries, 2015), (Oti & Tizani, 2015)
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 & Carter, 2013)
LEED is presently the leading and most widely adopted certification system in the USA and internationally	(Jalaei & Jrade, 2015), (Nguyen, et al., 2010)

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)
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 & Jrade, 2015)
It is interesting for designers to know in real time how their decisions are impacting the projects regarding environmental impacts and LEED certification possibility	(Jrade & Jalaei, 2013)
Three categories of LEED have direct relation with BIM: materials selection and use, systems analysis, and site selection and management	(Jalaei & Jrade, 2015),
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)
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)
It is not only viable but necessary to implement efficient energy models in new and existing urban areas	(Amado & Poggi, 2014)
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)
Incompatibilities were found comparing results obtained in the traditional way caused by outdated BIM models	(Azhar, et al., 2011)
The construction sector is the biggest responsible for CO_2 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 & Tizani, 2015)
The construction industry is the main villain of sustainable development due to all impacts it causes	(Nguyen, et al., 2010)
CO_2 emissions provide a basis for decision making regarding environmental impact	(Li, et al., 2012)
There is no available tool that dynamically calculates CO_2 emissions during construction	(Li, et al., 2012)
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)
Genetic algorithms are capable of handling the large amount of data found in the construction industry	(Inyim, et al., 2014)
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 & Tizani, 2015)
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 & Tizani, 2015)
Use of real data obtained from site with sensors enables a more accurate analysis	(Motawa & Carter, 2013)
The field of performance indicators is the most researched within the sustainability domain	(Oti & Tizani, 2015)
Little has been researched on decision support regarding greener constructions for structural projects	(Oti & Tizani, 2015)
The small number of reported experiments targeting sustainability assessment of the structural system was conducted only after construction finished, thus hindering changes	(Oti & Tizani, 2015)
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 & Poggi, 2014)
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)
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)

BIM based systems still lack interoperability, therefore designer intervention is still imperative	(Azhar, et al., 2010), (Salgueiro & Ferries, 2015)
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 & Krishnamurti, 2012)
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 & Krishnamurti, 2012)
Data exchange to sustanability tools is unidirectional, thus simulation tools are not able to feed data back to BIM platforms	(Motawa & Carter, 2013)
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 & Ferries, 2015)

2.3.2.3
Lean and Sustainability

Garza-Reyes (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. He also developed guidelines for future research over a table with a series of 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. They developed a framework of relationships and how these methods evolved to pitch in on greener constructions. They also propose better types of contracts and delivery methods to support sustainable constructions.

Based on the fact that sustainability guidelines consider all stages of the lifecycle of a building and so does LEED, Carneiro et al. (2012) analyzed 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, while not focusing on any specific industry. They basically looked 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 the execution stage. They also developed a framework to aid this implementation on future projects, envisioning to make this relationship a prevailing practice. Then, they explained 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 identified the gaps and needs in current practices. They then explored how these could be integrated on an operational level and included the waste management supply chain by proposing a Waste Flow Mapping (WFM) method, which they 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 studies 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, and they also understood the link between value from the project perspective and the global sustainability perspective.

Rosenbaum (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 syncronizing production with client needs.

Table 6 presents the main conclusions found by the authors from their research works. It also references where each finding can be encountered in the literature.

Table 6: Green-lean findings from the literature

Findings	References
Lean construction is the ideal approach to leverage sustainability value and integrate the delivery process by providing the foundation for sustainable delivery	(Novak, 2012)
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)
They share common tools and practices and overlap on: waste and waste reduction techniques, people and organisation, security, lead time reduction, supply chain relationship, efficiency, productivity, service level KPI	(Dues, et al., 2013), (Koranda, et al., 2012)
Lean economic improvement potentials coincided with environmental ones in this study (e.g. transport route reduction)	(Kurdve, et al., 2015)
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 & Kim, 2007), (Koranda, et al., 2012)
Previous studies identified lean and green integration as the best approach to minimize the environmental impacts of production	(Kurdve, et al., 2015)
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)
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)
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)
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)
The construction industry traditionally desagregates 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)
Waste classification is one of the most important approaches of the construction industry regarding environmental impacts	(Kurdve, et al., 2015)
Most lean construction studies focused specifically on the waste effects of poor planning of the construction process	(Lapinski, et al., 2006),
Construction performance is highly impacted by project constructability	(Rosenbaum, et al., 2014)

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 & Kim, 2007), (Lapinski, et al., 2006)
Social impacts of lean implementation are: work space security, ocuppant health, community well-being, participants loyalty and improved external image	(Bae & Kim, 2007)
Environmental impacts of lean implementation are: reduction of resource depletion, pollution prevention by waste elimination and resource preservation	(Bae & Kim, 2007)
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)
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)
Value Stream Mapping (VSM) and Life-Cycle Assessment (LCA) are the main lean and green tools, respectively	(Dues, et al., 2013)
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)
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)
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)
LEED certification system is an international reference, but its normativity does not provide the flexibility valued by lean construction	(Koranda, et al., 2012), (Carneiro, et al., 2012)
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)
Toyota was able to reach better green project results without going through LEED certification	(Koranda, et al., 2012)
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)
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)
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)
Communication and involvement of all stakeholders is of unparalleled importance to add value and accomplish a succesful project	(Koranda, et al., 2012), (Kurdve, et al., 2015), (Novak, 2012)
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),
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)

Many owners and design teams make mistakes at the beggining 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)
Visualization of scenario, reliable information sharing, easy comprehension, systematic and fast approaches are key points for lean tools	(Kurdve, et al., 2015)
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)
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 & Kim, 2007), (Rosenbaum, et al., 2014), (Novak, 2012)
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, e.g. lean practices do not necessairily reduce CO_2 emissions (Just in Time (JIT) is an example that usually causes the exact opposite)	(Dues, et al., 2013), (Koranda, et al., 2012)
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)
Only a small number of tools have been developed targeting production managers and environmental engineers	(Kurdve, et al., 2015)
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)
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)
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)

3
Integration Analysis and Proposed Methodology Implementation

3.1
Integration Analysis of BIM, Lean and Sustainability

Based on an analysis of study goals and the observed findings from the literature review, a framework is proposed (in Table 9), to integrate BIM functionalities and lean methodology principles to support more sustainable constructions. The framework is adapted from the BIM-lean integration matrix proposed by Sacks et al. (2010) and is presented following tables 7 and 8.

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) BIM, lean and sustainability interactions, further numbered to be described. Table 7 and Table 8 explain row and column keys respectively to ease reader understanding.

Table 7: BIM Functionalities

BIM functionalities		Row
Visualization of form	Aesthetic and functional evaluation	1
Rapid generation of multiple 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 8: Lean Principles

Lean principles		Column
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)

Table 9: BIM, Lean and Green integration matrix

BIM Fuctionalities \ Lean Principles		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													13				13					13	
Rapid generation of design alternatives	**2**	1		9	(7)		10									14				2				17	
Re-use of model data for predictive analysis	**3**	2	2	9			10												1	2		16		17	
	4			9												14				2					
	5	1	1	9															1	1	1	16		17	
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**															14									
	10	4		9				9																17	
Rapid generation and evaluation of multiple construction plan alternatives	**11**				(7)																				
	12				(7)																				
	13	5	5	5	(7)						11		5	5											
Online/electronic object based communication	**14**		7														(15)								
	15										11		11				(15)								
	16	6					6										(15)								
	17		13														(15)								
	18											12					(15)								

Adapted from Sacks et al. (2010)

The following list highlights the main interactions that could be drawn from the literature review of theoretical, empirical and methodological studies regarding combinations of BIM, Lean and Sustainability aspects:

1. BIM provides better appreciation of design at early stages due to its capability of fast generating of multiple design alternatives. This enables early sustainability assessments against performance criteria (e.g. energy) and, thus, earlier design adjustments. Consequently, this reduces the variability commonly present due to late changes regarding environmental concerns during construction, making the quality of the end product higher and less prone to rework;
2. At the conceptual stage, fast generation of design options to prepare cost estimates and sustainability related assessments (energy, lightning, etc) allow evaluation of multiple alternatives of design through re-use of data extracted from BIM models, including the use of optimization algorithms such as genetic algorithms, as proposed by Inyim et al. (2014). This ensures it is appropriate and optimized for the designated function, which consequently reduces variability and improves product quality;
3. Conventional methods of design development based on 2D drawings require multiple representations of a single object in unconnected documents (e.g. top view, south view). This creates a challenge in maintaining design consistency when design changes are made. Usually, many of the inconsistencies resulted from this challenge are only perceived late on construction sites, which in turn causes rework that generates 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). BIM provides a solution for this challenge by concentrating all design related information on a centralized model from which drawings are automatically generated;
4. Sustainable construction developments require intensive interdisciplinary collaboration and the involvement of all stakeholders in order to add more value to the project. Building modeling imposes a rigor on designers in that flaws or incompletely detailed parts are easily found in clash checking or other automated checking. If this were a manual process, it would require intensive work, iterations and time, and would still not be able to predict all problems.

This improves design quality, reduces cycle times (production duration) and in turn reduces field rework that not only causes delays, but also impacts the economic and environmental aspects of sustainability;

5. 4D visualization of construction schedules provided by BIM signifcantly reduces occurrences of activity and equipment conflicts during construction in time and space (temporal clash detection). This improves worker safety, increases efficiency, reduces schedule variability and reduces cycle times (production duration) during the construction. Therefore, it reduces delays and consequently financial wastes, thus positively impacting the economic and social aspects of sustainability;
6. Direct transfer of object information details from the model to numerically-controlled machinery diminishes chances for human error and not only improves product quality, but also enables fabrication of more complex products. Besides this, it also reduces the setup time (time spent on data entry for fabrication purposes). This is particularly interesting for "greener" components, which are often more difficult to fabricate and demand higher precision;
7. This interaction was considered negative, because according to Khemlani (2009), an increase in the inventory of design and construction plan alternatives is bad considering the lean principle of "reduce inventory". On the other hand, it can be considered beneficial for the decision making process in terms of making broader selections, delaying selection of a single alternative until the last possible moment. This can be specifically important for sustainability, since it requires consideration of design alternatives until a close to optimal solution is achieved in terms of performance and environmental impact;
8. Live connections with partner (supply chain) databases significantly decrease waiting time, thus improving flow. With this, designers would be able to test different components from different suppliers in real time and understand how the use of certain components are impacting the project in terms of environmental impact and costs. This will provide a possibility for designers to test multiple alternatives on the go, thus ensuring a more sustainable design;
9. An important requirement of sustainable construction is to have a collaborative project process to enable quick design changes and fast re-evaluation of structural, thermal and energy analyes; cost estimations; and conformance to

client values. This imposes a challenge to the traditional project process, because designers would hardly go through the process of altering every single document every time a change was made. BIM not only requires this integration of stakeholders, but also allows automatic generation of drawings, consequently reducing cycle time for building design and detailing.

10. Flexibility is increased by using BIM because it allows the use of model data to iteratively run various and more detailed sustainability analyses within different design alternatives without deeply compromising setup time. Thus, contributes to a better design in terms of performance and environment impact;
11. BIM methodology and tools can provide ways of simulating the production and assembling sequence, which in turn can guide workers on how to perform certain activities in the best way following company standards. 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;
12. According to Novak (2012) and Koranda et al. (2012), labor inefficiency should be considered a source of waste by sustainability. This way, it is particularly important to achieve continuous process improvements. BIM tools can be one way to achieve that considering they allow live status reports, thus measurements of labor performance becomes viable and documented.
13. 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 the understanding of projects, providing ground for more complex products. The simplification in visualization enabled by the 3D model also allows the client to ensure all his requirements (values) are met. This is extremely important for sustainable designs and allows other participants to take part in the decision making process;
14. BIM provides the possibility of multi-skilled teams to work at the same time aiming at generating different design alternatives early in the project phase. This is particularly important for sustainable projects to find a near optimal solution without compromising much time;
15. Online/electronic object-based communication can be considered a setback

in terms of technology reliability, because BIM tools are not yet mature enough to be fully automated. Instead of being benefitial, it could become a source of unclear communication and, thus, generate wastes.

16. Simulations based on the intelligence built in the model objects viabilize automatic checking against sustainability regulations, improving efficiency during verification and validation;
17. These functions facilitate collaborative decision making by providing transparent information to 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.

3.2
Plug-in

In order to explore, validate and verify some of the encountered interrelationships, a prototype plug-in is proposed aiming at implementing an indicator based system to support design decision making through automatic extraction of model data and conduction of sustainable assessments. With this plug-in, interactions 1, 2, 9, 10 and 13 of the framework are explored.

The intention is to provide a BIM integrated system that will aid evaluation of multiple design alternatives mainly focusing on the conceptual stage as idealized by lean principles and required for better sustainable project developments.

According to Oti and Tizani (2015), the structural engineering domain still lacks sustainability decision support tools for guiding engineers and architects in early design iterations. Current sustainability assessments have been based on the completed structure. This apparently compromises the usefulness of sustainability ratings in design-decisions making process.

In the planning and design stages, the benefits of the early incorporation of sustainability principles in guiding project decisions and design iterations have been well emphasized in the literature (Oti & Tizani, 2015). One challenge has been the development of sustainability appraisal tools to guide professionals in making conceptual design decisions among alternative solutions. The need is, therefore, to establish quantitative terms for qualifying sustainability and to consider it right at the early stages of the project development process to guide decisions as progress is made.

The developed system incorporates Life Cycle Cost (LCC), Life Cycle CO_2 Emission (LCCE) and Thermal Comfort based on heat flow indicators. However, it can be extended to incorporate other indicators to enable increasingly reliable and efficient decision support. It also allows for better consideration of what in fact generates value to the customer by enabling user inputs of varying weightings to indicators (e.g. higher weight to LCC than LCCE if the user is more concerned with costs than environmental impact).

Chosen metrics are based on the fact that CO_2 emissions are increasingly being considered by researchers as a prime measure of environmental impact and that the construction industry is the main responsible for such emissions. Despite being a common knowledge that cost is always a concern not only for sustainable development, but also to clients, a certain lack of concern with economic aspects could be perceived within the analyzed studies.

Figure 6 presents the overall flow of the prototype and indicates where a more detailed description of each step can be found.

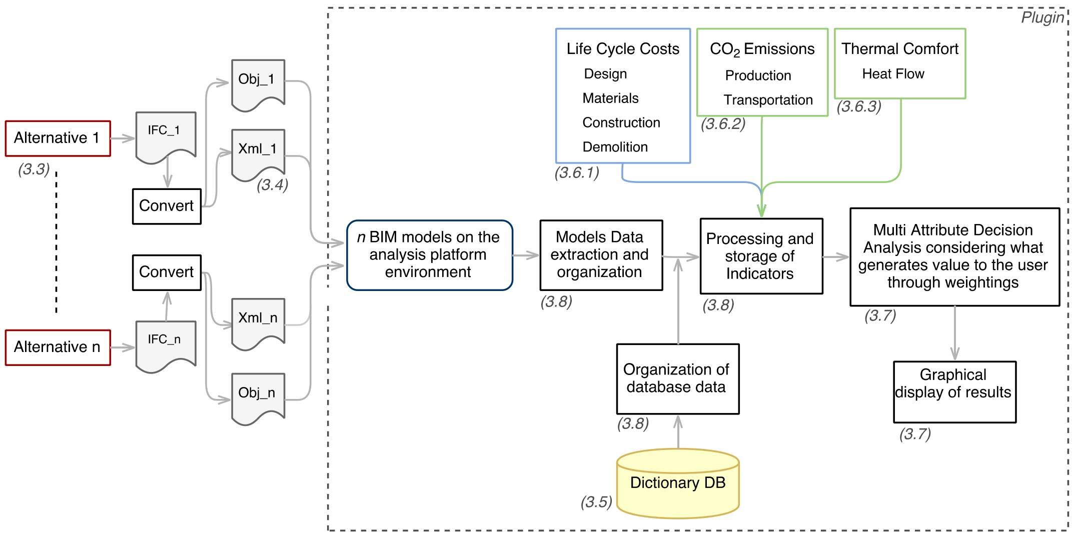

Figure 6: Flowchart of the proposed implementation with indication of text explanations

3.3 Hypothetical Examples

To illustrate the usability and effectiveness of the proposed methodology, a hypothetical situation was created as an example. In this situation, a particular client needed to build a warehouse that could be constituted of different combinations of materials and forms, while maintaining an average floor area of $1650m^2$.

To that end, four hypothetical warehouses were developed seeking to mainly comprise different structural framing tipology possibilities, while also considering varied types of roofs, walls, slabs and dimensions.

Even though the focus of this work is not on structural modeling, to guarantee that examples were somewhat realistic, all four of them were initially pre-dimensioned following literature reccomendations and then modeled and calculated on *Autodesk Robot Structural Analysis* to make sure displacements did not surpass design code limits and sections were correctly dimensioned to support loads. To illustrate how the dimensioning process was conducted, one of the examples is thoroughly explained on section 3.3.2.

Models were iteratively sent back and forth between *Autodesk Revit* and *Autodesk Robot* until all components were correctly placed. This was only possible thanks to the direct data and geometry integration built in these softwares. Complete models are presented on section 3.3.3, where features of each design option, including structure dimensions, are listed.

3.3.1 Structural Pre-dimensioning

For the four hypothetical examples, three diferente types of structural solutions were considered:

- Examples one and four are steel truss-based solution and were dimensioned using the abacus developed by Bareiro (2015);
- Example two is based on solid steel beams and columns and was dimensioned using Gerdau’s (2012) warehouse manual;
- Example three presents a solution based on pre-cast concrete elements and was dimensioned based on the studies by Camillo (2010) and Queiros (2007).

All structural design options were initially modeled in *Autodesk Robot* considering fixed supports and are presented on Figures 7, 8, 9 and 10.

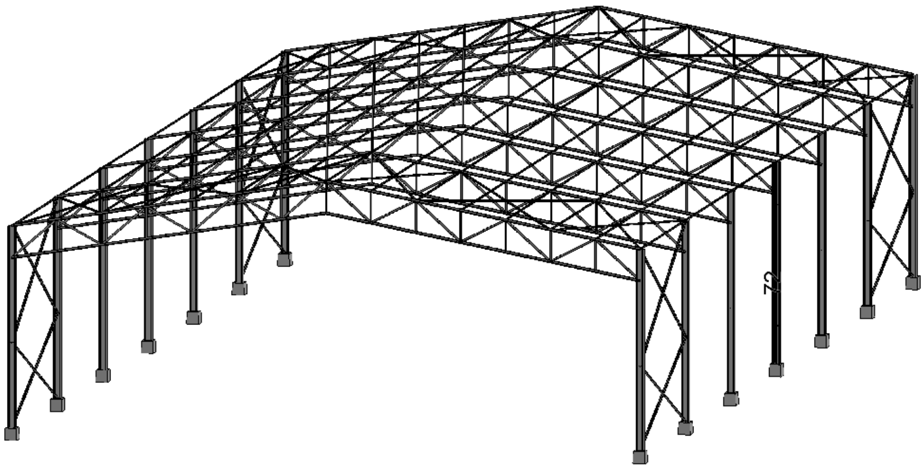

Figure 7: Structural design of hypothetical example 1 (steel truss framing with parallel uprights)

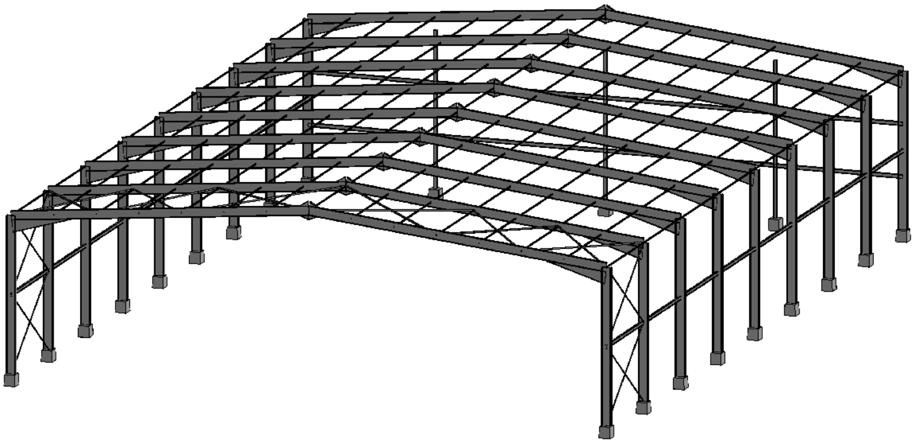

Figure 8: Structural design of hypothetical example 2 (steel framing with solid section)

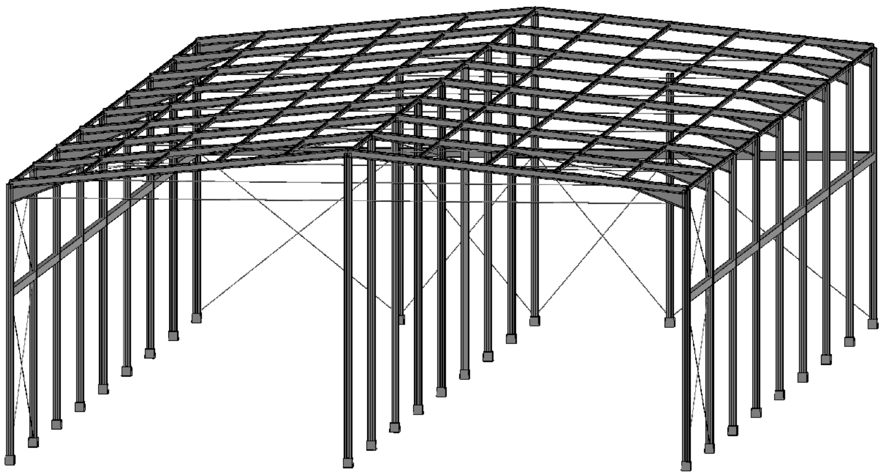

Figure 9: Structural design of hypothetical example 3 (pre-cast concrete framing)

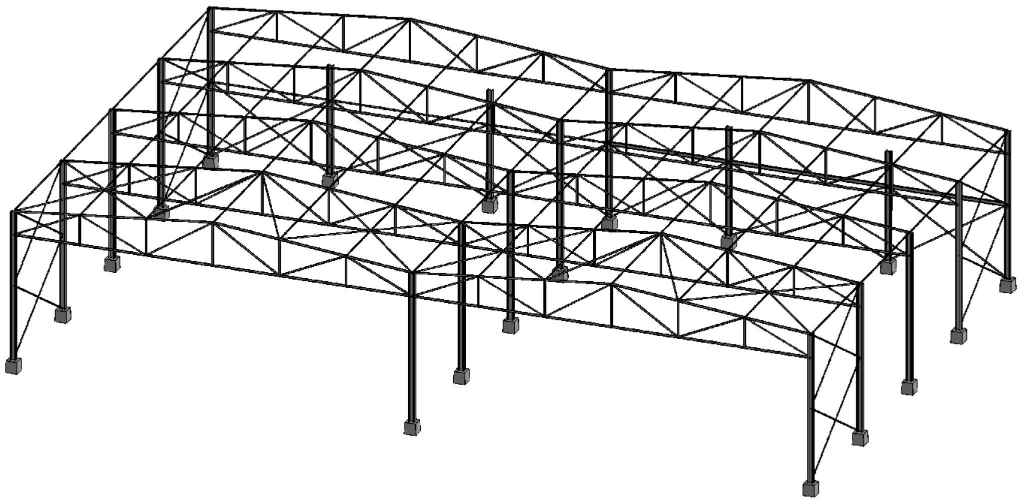

Figure 10: Structural design of hypothetical example 4 (double span steel truss framing with trapezoidal uprights)

3.3.2 Verification

The calculation procedures for dimensioning structural systems are laborious and may consume considerable time of the structural engineer. Current commercial software allow partial automation of this stage, allowing the engineer to devote more time to the analysis and design optimization of structures (Bareiro, 2015).

This section presents procedures and results regarding verification of pre-dimensioning the structure of hypothetical example 1. It took advantage of the fast analysis capability enabled by *Autodesk Robot Structural Analysis* combined with Brazilian standard for Design of Steel Structures (NBR8800:2008).

3.3.2.1 Working Loads

Permanent loads are those that present almost constant values during the lifetime of the edification. In this example, these are:

- Dead load of the structure (DL1): automatically calculated by the software;
- Permanent load (DL2): in this case is the effect of the roof, since purlins, bracings and other elements are already considered by the software within the dead load (0,30kN/m^2);
- Notional force (Nforce): an equivalent force of 0,3% of the total gravitational load value is applied (0,81kN). The notional force is used

to consider geometry imperfections of the structure and is applied laterally on columns of each floor;

Accidental loads are used to take into account overlaps that might damage the roof:

- Accidental load (ACC1): this value is determined according to NBR8800:2008 (0,25kN/m^2).

Wind loads seek to consider occasional effects of wind on the structure, these are:

- Forces caused by 0º winds (WIND1): this value is calculated according to NBR6123:1988. This example considered a wind speed of 45m/s and terrain category III, which resulted in suction of the roof;
- Forces caused by 90º winds (WIND2): calculated adopting the same considerations of 0º winds. The effect also resulted in suction of the roof.

Table 10: Wind loads of hypothetical example 1

	Column 1 (kN/m)			Column 2 (kN/m)		
	1 to 3m	3 to 6m	6 to 8m	1 to 3m	3 to 6m	6 to 8m
0º Wind	6,62	7,63	8,35	6,62	7,63	8,35
90º Wind	3,31	3,82	4,17	4,63	5,34	5,84
	Roof 1 (kN/m)			Roof 2 (kN/m)		
0º Wind	8,91			8,91		
90º Wind	12,47			6,24		

All distributed loads (kN/m) were applied as linear loads on columns and as nodal loads on the truss.

3.3.2.2
Load Combinations

Load combinations were defined according to the prescriptions of NBR8800:2008.

Ultimate Limit State (ULS) combinations were used to verify the resistance of the structural elements and were defined according to item 4.7.7.2 of NBR8800:2008. Considering warehouses as “locals without high concentration of people”, the following combinations were prescribed:

COMB1 (ULS) = 1,25*DL1 + 1,50*DL2 + 1,50*ACC1 + Nforce

COMB2 (ULS) = 1,00*DL1 + 1,00*DL2 + 1,40*WIND1

COMB3 (ULS) = 1,00*DL1 + 1,00*DL2 + 1,40*WIND2

Service Limit State (SLS) combinations were used to verify structure displacements and were defined according to item 4.7.7.3 of NBR8800:2008. The following combinations were prescribed:

COMB4 (SLS) = 1,00*DL1 + 1,00*DL2 + 0,70*ACC1

COMB5 (SLS) = 1,00*DL1 + 1,00*DL2 + 1,00*WIND1 + 0,70*ACC1

COMB6 (SLS) = 1,00*DL1 + 1,00*DL2 + 1,00*WIND2 + 0,70*ACC1

3.3.2.3
Structural Analysis Results

After working loads and combinations were correctly defined and configured in *Autodesk Robot*, the next step was to perform the analyses followed by dimensioning using the *Steel Design* module. First, it was necessary to configure displacement limits. From that, the software automatically verified and generated reports on whether the defined sections were "ok" or if they needed to be changed based on the "ULS" and "SLS" combinations.

Figure 11 shows an example of software results indicating columns being rejected for not presenting the required resistance (ULS). After changing the columns, Figure 12 shows results indicating successful results for both displacements and resistances (SLS and ULS). Finally, Figure 13 shows an example of successful displacement verification of chords.

Calculation reports are presented in Appendix A, on Figures A-1, A-2, A-3 and A-4.

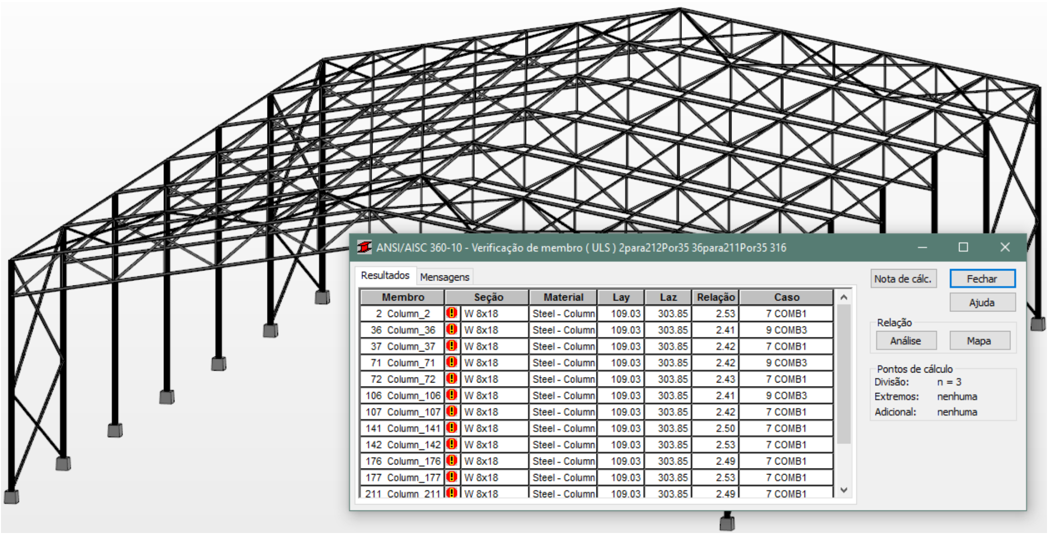

Figure 11: Example of rejected column sections based on resistance (ULS)

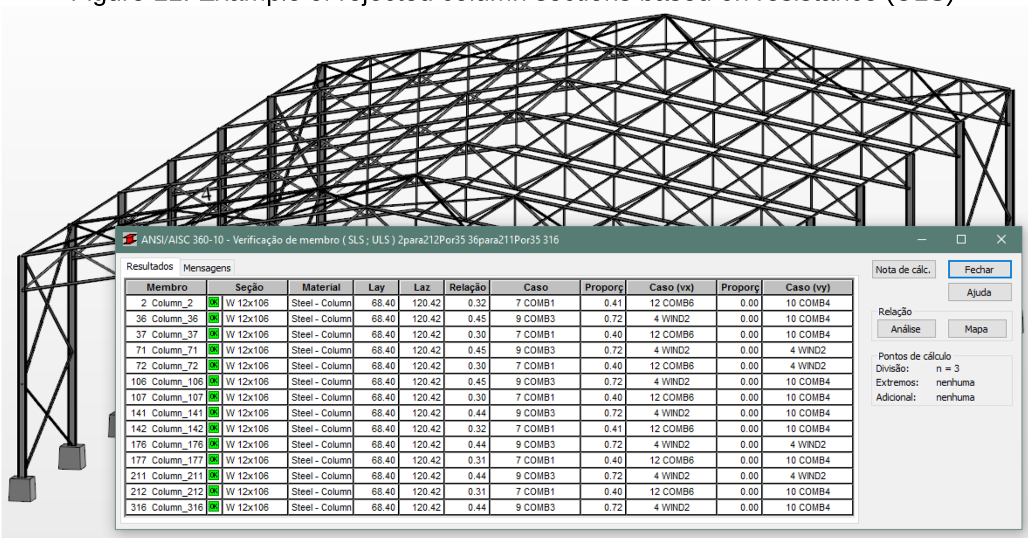

Figure 12: Resistance (ULS) and displacement (SLS) columns verification

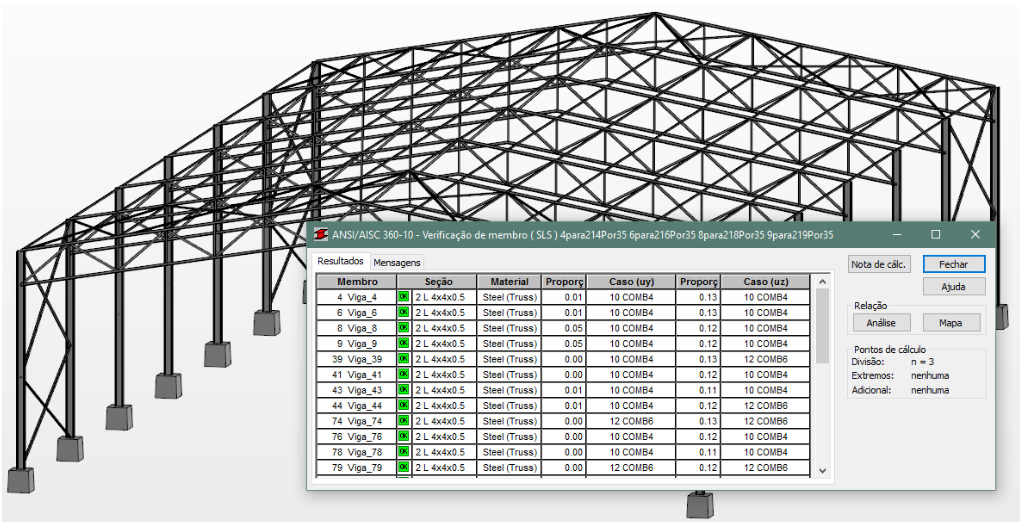

Figure 13: Displacement (SLS) verification of chords

3.3.3 Design Options

After dimensioning each structure, the models were directly integrated into *Autodesk Revit*, where architectural components were chosen and added to the model. Each modeled design choice is illustrated in Figures 14, 15, 16 and 17, followed by a list describing its features.

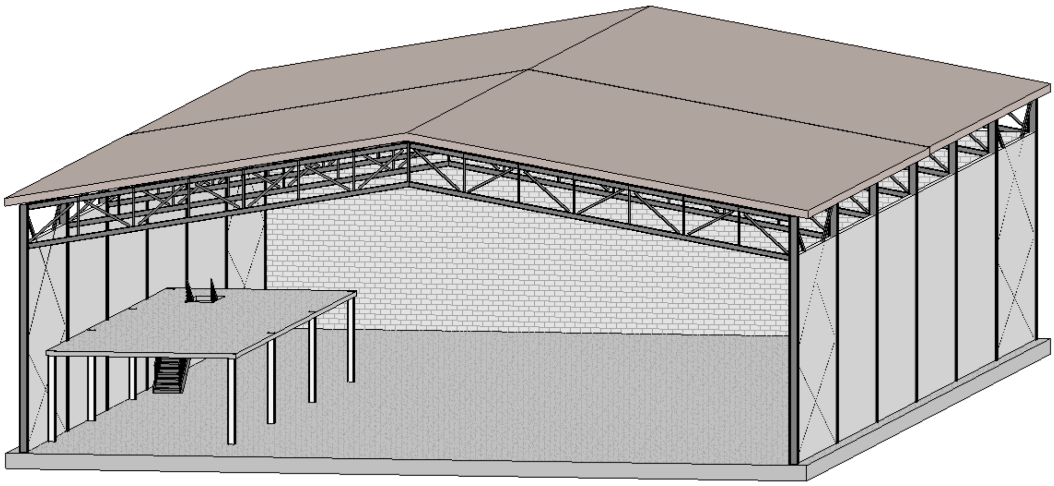

Figure 14: Hypothetical example 1

Design 1:

- Steel truss framing with parallel uprights
- 30m span
- 54m length with 9m spacing between frames
- Ceramic tiles roof
- Concrete brick walls
- Cast in place concrete floor
- Cast in place concrete mezanine with steel framing structure
- Columns – W 12x106
- Vertical posts – L 2,5x2,5x0,5 and Diagonals – L 3,5x3x0,5
- Chords – DL 4x4x0,5
- Purlins – C 3x5
- Bracings – DL 2,5x2,5x0,25

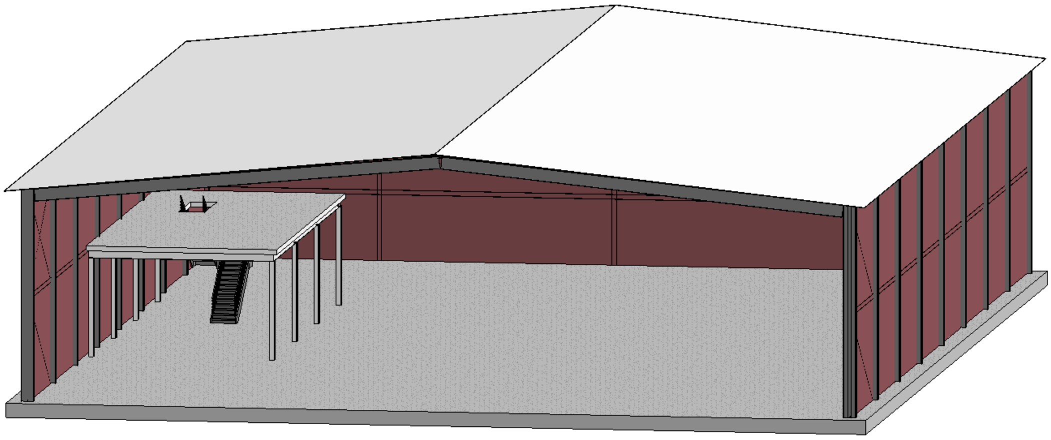

Figure 15: Hypothetical example 2

Design 2:

- Steel framing with solid section beams
- 35m span
- 48m length with 6m spacing between frames
- Aluminum tiles roof e=0,6
- Ceramic brick walls
- Cast in place concrete floor
- Steel deck mezanine with steel framing structure
- Columns – W 21x73
- Secondary colums – W 10x22
- Beams – W 21x48
- Secondary beams – W 8x18
- Purlins – C 3x6
- Bracings – DL 3x3x0,25

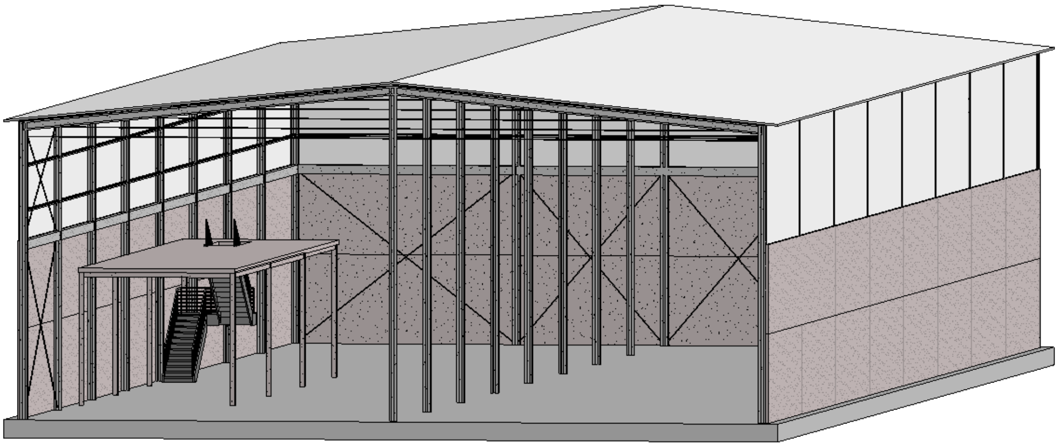

Figure 16: Hypothetical example 3

Design 3:

- Pre-cast concrete structure
- 25m span with mid-column
- 64m length with 8m spacing between frames
- Polyurethane filled aluminum tile roof
- Cement pannel complemented with steel deck walls
- Cast in place concrete floor
- Pre-cast concrete mezanine with pre-cast concrete framing structure
- Columns – B=30cm, b=12cm, H=30cm, h=9cm
- Beams – B=23cm, b=16cm, H=35cm, h=6cm
- Secondary beams – B=20cm, H=30cm
- Purlins – T shape, B=10cm, b=4cm, H=15cm, h=5cm
- Bracings – 25mm steel bar
- Pre-cast concrete 40 Mpa

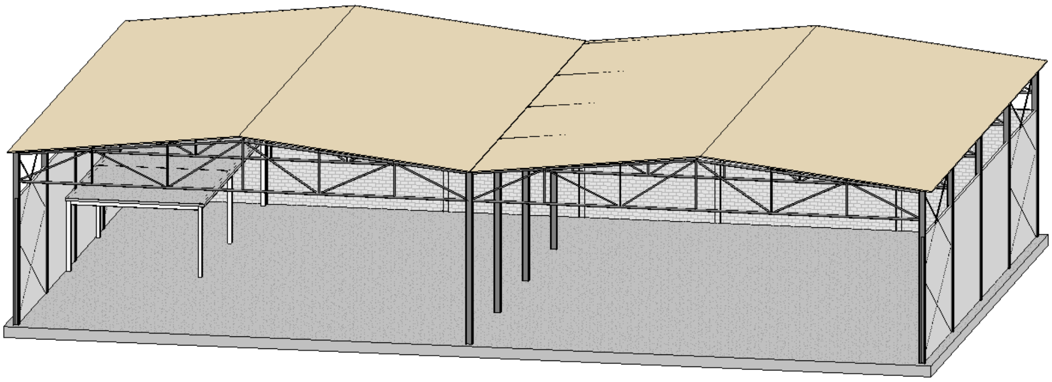

Figure 17: Hypothetical example 4

Design 4:

- Steel truss framing with trapezoidal uprights
- 2 spans of 25m each
- 32m length with 8m spacing between frames
- Concrete tiles roof
- Concrete brick walls
- Cast in place concrete floor
- Cast in place concrete mezanine with pre-cast concrete framing structure
- Columns – W 12x87
- Central Columns – W 12x120
- Vertical posts – 3x3x0,25 and Diagonals – L 3x3x0,375
- Chords – DL 4x3x0,625
- Purlins – C 3x6
- Bracings – L 3x2x0,3125
- Mezanine with precast concrete structure

3.3.4
Integration Barriers

The integration between *Autodesk* systems *Robot and Revit* can be done directly, and does not require an intermediate format for exportation and importation. However, some problems were detected during the exchange process i.e.:

- Connections and reinforcements (as illustrated on Figure 8 and 9) modeled on *Autodesk Robot* that were not recognized when imported on *Autodesk Revit* (Figures 15 and 16);
- Double L-shaped sections that caused *Autodesk Revit* to crash whenever any of those was present on a model generated in *Autodesk Robot*;
- Some sections available to be assigned on the *Autodesk Robot* database could not be verified when dimensioning calculations were undertaken.

To work around the double L-shaped sections problem, they were substituted by sections with the same equivalent area whenever the model was exported to *Autodesk Revit*, this way not influencing on the proposed system results.

3.4
IFC Import

After the models were finalized, files were exported from *Autodesk Revit* to an Industry Foundation Classes (IFC) file developed by BuildingSMART containing geometry and object attribute data. This schema aims to estabilish a single format of information flow between systems to ease interoperability, which is one of the most proeminent barriers for industry adoption of BIM, since there is no one system that is capable of doing everything.

The available commercial softwares that are capable of supporting plug-ins were *Autodesk Revit* and *Autodesk Navisworks*. But since it is not possible to load multiple projects on the same environment side-by-side with a clear differentiation of which element corresponds to which model, these softwares could not be used. The platform used for this research was *Environ*, a 3D engineering data visualization and analysis non-commercial software developed by the Tecgraf/PUC-Rio Institute mainly to support project automation of industrial plants.

Since the platform was not yet capable of reading an *ifc* file, it was necessary to first convert this *ifc* into an *obj* file (a geometry definition file format containing the triangle mesh-based geometry) and an *xml* file (an attribute definition file format). The *obj* could already be imported by the platform, while the *xml* could not. This *ifc* to *obj* and *xml* conversion was accomplished with the IfcOpenShell's IfcConvert open source program.

With these two files in hand, it was possible to observe that each object in the xml file contained a unique tag that related to a unique object in the obj file with the same tag. Besides, each object in the xml file contains a list of references that points to a single attribute previously defined on the xml file as illustrated in Figure 18.

Knowing this, what had to be done was to relate each object and its properties of the xml file with their respective geometry that was already represented in the platform. The implementation code of this association is presented on Appendix B.

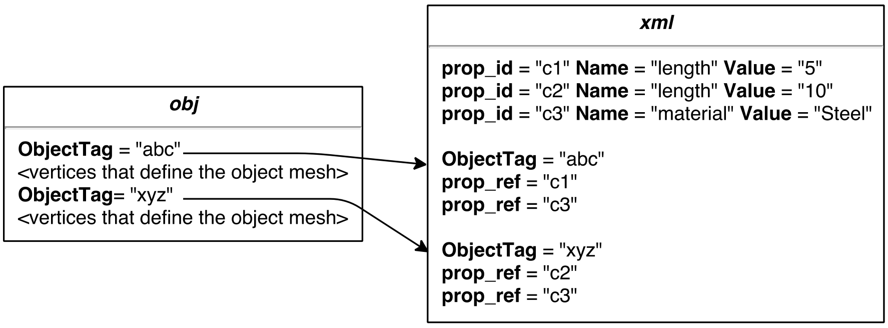

Figure 18: obj and xml files connection

After the association was properly conducted, all four models could be simultaneously loaded on a single platform environment (which is not possible in Autodesk Revit) as illustrated on Figure 19. Whenever an object is selected, its attributes and associated values retrieved from the IFC file are shown on the right hand side window.

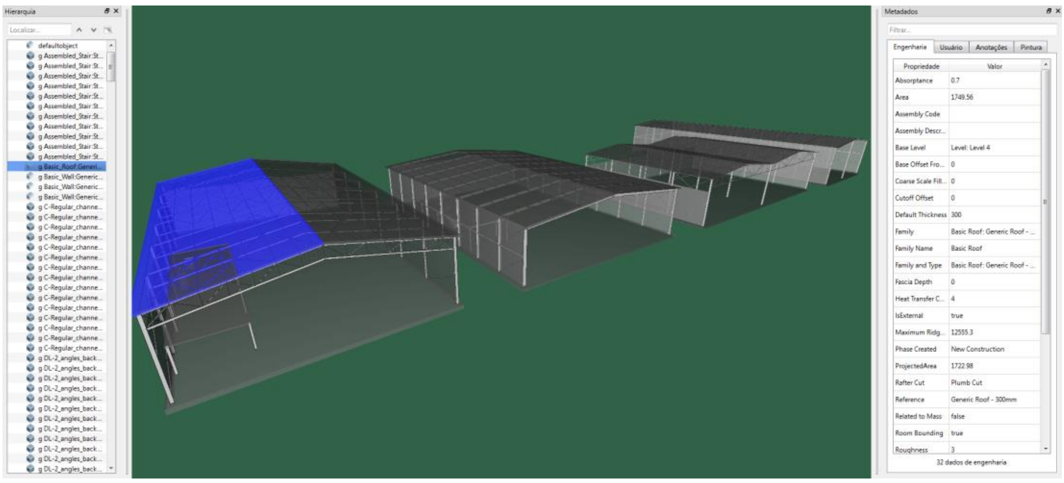

Figure 19: View of models and object properties into the platform

3.5
Dictionary Database

The dictionary database is a *Microsoft Excel* file developed by the author (because most of the data was only available on non-computable *pdf* files) and composed of multiple sheets, containing data on costs, CO_2 emissions and thermal properties. The sources of gas emission data are mainly Costa (2012) and ICE database, while cost data was primarily obtained from Brazilian government's SINAPI and thermal data was gathered both directly from the *ifc* file exported by *Autodesk Revit* or from NBR15220::2005.

The dictionary was developed as a spreadsheet instead of embedded in the plug-in in order to facilitate updating of values and insertion of new data as necessary. Whenever the plug-in starts this small database is imported and read. A piece of the mentioned developed database is depicted in Figure 20.

	A	B	C	D	E	F	G	H	I	J
1	ID	Material	ICE cradle to ga	Unit	EnergyToManu	Unit	EFManufacture	Unit	EFReaction	Unit
2	1	Aluminum	9.080	tCO2/t	154.00	MJ/kg	3.851	tCO2/t	0.006	tCO2/t
3	2	Cement	0.950	tCO2/t	5.50	MJ/kg	0.296	tCO2/t	0.332	tCO2/t
4	3	Cement Brick	0.740	tCO2/t	4.51	MJ/kg			0.000	tCO2/t
5	4	Cement plaster external							0.000	tCO2/t
6	5	Cement plaster internal							0.000	tCO2/t
7	6	Ceramic Brick	0.700	tCO2/t	10.00	MJ/kg	0.058	tCO2/t	0.033	tCO2/t
8	7	Ceramic Cladding	0.780	tCO2/t	12.00	MJ/kg	0.058	tCO2/t	0.033	tCO2/t
9	8	Ceramic Roof Tile	0.780	tCO2/t	12.00	MJ/kg	0.058	tCO2/t	0.033	tCO2/t
10	9	Clay Brick	0.240	tCO2/t	3.00	MJ/kg			0.000	tCO2/t
11	10	Clay Tile	0.480	tCO2/t	6.50	MJ/kg			0.000	tCO2/t
12	11	Concrete Brick 08 Mpa	0.063	tCO2/t	0.59	MJ/kg			0.000	tCO2/t
13	12	Concrete Brick 10 Mpa	0.078	tCO2/t	0.67	MJ/kg			0.000	tCO2/t
14	13	Concrete Brick 12 Mpa	0.088	tCO2/t	0.72	MJ/kg			0.000	tCO2/t
15	14	Concrete Brick 13 Mpa	0.107	tCO2/t	0.83	MJ/kg			0.000	tCO2/t
16	15	Concrete general 06/08 Mpa	0.069	tCO2/t	0.31	MJ/kg	0.102	tCO2/t	0.000	tCO2/t
17	16	Concrete general 08/10 Mpa	0.087	tCO2/t	0.39	MJ/kg	0.129	tCO2/t	0.000	tCO2/t
18	17	Concrete general 12/15 Mpa	0.094	tCO2/t	0.67	MJ/kg	0.137	tCO2/t	0.000	tCO2/t
19	18	Concrete general 16/20 Mpa	0.100	tCO2/t	0.70	MJ/kg	0.147	tCO2/t	0.000	tCO2/t
20	19	Concrete general 20/25 Mpa	0.107	tCO2/t	0.74	MJ/kg	0.150	tCO2/t	0.000	tCO2/t
21	20	Concrete general 25/30 Mpa	0.113	tCO2/t	0.78	MJ/kg	0.161	tCO2/t	0.000	tCO2/t
22	21	Concrete general 28/35 Mpa	0.120	tCO2/t	0.82	MJ/kg	0.168	tCO2/t	0.000	tCO2/t
23	22	Concrete general 32/40 Mpa	0.132	tCO2/t	0.88	MJ/kg	0.177	tCO2/t	0.000	tCO2/t
24	23	Concrete general 40/50 Mpa	0.151	tCO2/t	1.00	MJ/kg	0.188	tCO2/t	0.000	tCO2/t
25	24	Concrete precast 06/08 Mpa	0.105	tCO2/t	0.55	MJ/kg	0.165	tCO2/t	0.000	tCO2/t
26	25	Concrete precast 08/10 Mpa	0.133	tCO2/t	0.70	MJ/kg	0.183	tCO2/t	0.000	tCO2/t
27	26	Concrete precast 12/15 Mpa	0.143	tCO2/t	1.00	MJ/kg	0.191	tCO2/t	0.000	tCO2/t
28	27	Concrete precast 16/20 Mpa	0.152	tCO2/t	1.15	MJ/kg	0.196	tCO2/t	0.000	tCO2/t
29	28	Concrete precast 20/25 Mpa	0.161	tCO2/t	1.21	MJ/kg	0.200	tCO2/t	0.000	tCO2/t
30	29	Concrete precast 25/30 Mpa	0.169	tCO2/t	1.26	MJ/kg	0.203	tCO2/t	0.000	tCO2/t
31	30	Concrete precast 28/35 Mpa	0.177	tCO2/t	1.31	MJ/kg	0.216	tCO2/t	0.000	tCO2/t
32	31	Concrete precast 32/40 Mpa	0.192	tCO2/t	1.36	MJ/kg	0.223	tCO2/t	0.000	tCO2/t
33	32	Concrete precast 40/50 Mpa	0.217	tCO2/t	1.40	MJ/kg	0.231	tCO2/t	0.000	tCO2/t
34	33	Concrete ready mix 06/08 Mpa	0.076	tCO2/t	0.55	MJ/kg	0.112	tCO2/t	0.000	tCO2/t
35	34	Concrete ready mix 08/10 Mpa	0.104	tCO2/t	0.70	MJ/kg	0.135	tCO2/t	0.000	tCO2/t
36	35	Concrete ready mix 12/15 Mpa	0.114	tCO2/t	0.76	MJ/kg	0.145	tCO2/t	0.000	tCO2/t
37	36	Concrete ready mix 16/20 Mpa	0.123	tCO2/t	0.81	MJ/kg	0.150	tCO2/t	0.000	tCO2/t
38	37	Concrete ready mix 20/25 Mpa	0.132	tCO2/t	0.86	MJ/kg	0.154	tCO2/t	0.000	tCO2/t
39	38	Concrete ready mix 25/30 Mpa	0.140	tCO2/t	0.91	MJ/kg	0.157	tCO2/t	0.000	tCO2/t
40	39	Concrete ready mix 28/35 Mpa	0.148	tCO2/t	0.95	MJ/kg	0.170	tCO2/t	0.000	tCO2/t
41	40	Concrete ready mix 32/40 Mpa	0.163	tCO2/t	1.03	MJ/kg	0.177	tCO2/t	0.000	tCO2/t
42	41	Concrete ready mix 40/50 Mpa	0.188	tCO2/t	1.17	MJ/kg	0.196	tCO2/t	0.000	tCO2/t
43	42	Fibre Cement Panel Coated	1.280	tCO2/t	15.30	MJ/kg			0.000	tCO2/t
44	43	Fibre Cement Panel Uncoated	1.090	tCO2/t	10.40	MJ/kg			0.000	tCO2/t
45	44	Glass	0.910	tCO2/t	15.00	MJ/kg	0.608	tCO2/t	0.192	tCO2/t

- | CO2 Material | CO2 Fuel | Transport Consumption | Transport Material | Cost Acitivities | Cost Material

Figure 20: Part of the designed dictionary database

3.6 Indicators

For the purpose of testing the proposed method, Life Cycle Costing (LCC) and CO_2 emissions were implemented as the main indicators to evaluate the example models. This is because they represent economic and environmental aspects of sustainability, and according to the BIM Task Group (2011), whole life cost and carbon performance were identified as the key variables that can influence building sustainability performance significantly. Thermal comfort based on heat flow was also incorporated in order to give even more weight on the environmental side of sustainability.

LCC and LCA in the construction industry have developed separately in response to economic and environmental problems, but the two have much in common. Some similarities are that both LCC and LCA utilize data on quantities and specification of materials used (e.g. thickness, amount), maintenance and operational implications of using the products, and end of life demolition. On the other hand, the main difference is that LCC methods do not take into consideration the process of making a product; they are concerned with the market cost, while LCA takes production into consideration when considering embodied energy.

The Task Group 4’s (2003) final report on Life Cycle Costs in construction stated that combining economic and environmental assessment tools to obtain "best value" solutions in both financial and environmental terms has the potential to make a significant contribution to achieving sustainable development.

3.6.1 Life Cycle Costing

Life cycle costing (LCC) is a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational costs. In particular, it is an economic assessment considering all projected relevant costs over a period of analysis expressed in monetary value. Where the term uses initial capital letters it can be defined as the present value of the total cost of an asset over the period of analysis (TG4).

In the early conceptual stages, which are analyzed in this study, it will only provide a broad estimate of the costs, but when decisions are made and the design details defined, it will provide an increasingly more reliable prediction of the total cost of owning and operating the asset.

To determine overall costs of each hypothetical model assessed in this study, the following stages were considered: design development, material acquisition, construction acitvities and demolition. Calculation were made element by element and incremented until all elements had been considered. This enables considering the cases which have multiple types of materials within elements of a single category.

3.6.1.1
Design Development Costs

Costs regarding design development are usually defined as a fraction of project costs and decrease as the volume or weight increases (e.g. for steel if the total weight of beams is under 12 ton, design cost will be 9.6% of project costs; if it falls between 12 and 25 ton, design cost will be 9%).

Therefore, for each material within that category, the total volume (or weight depending on material) of elements is calculated to determine the applicable range and, thus, enabling design cost calculations. Equations 1 and 2 apply to Columns, Beams and Slabs.

$$V = \sum V_e \quad (1)$$

$$DE_C = \sum \left(MA_C \times RA_P \times \frac{V_e}{V} \right) \quad (2)$$

Where:

DE_C = design cost of the category in Brazilian currency (R$);

MA_C = material cost of the category in R$;

RA_P = cost of the design in percentage, dependent on the range it falls into;

V_e = volume of the element in m^3 (may be W_e in kg, depending on material);

V = total volume of the category in m^3 (may be W in kg depending on material).

Roofs and Walls present fixed design costs, only dependent on the total area of each category. This cost is calculated as given by Equation 3.

$$DE_C = \sum (MT_C \times A_e) \quad (3)$$

Where:

DE_C = design cost of the category in Brazilian currency (R$);

MT_C = cost of the material design in R$/m²;

A_e = area of the element in m².

Total design costs of each model are then calculated as the summation of design costs per category. Since design costs depend on the value of material costs, they are calculated afterwards. However, they are presented first in the results.

3.6.1.2
Material Acquisition Costs

Material costs are calculated basically based on volume, weight and/or area of each element, depending on type of material and its category, as presented in Equations 4, 5, 6 and 7. Calculations also consider the average factor of material loss on site, found in the literature for each type of construction material.

$$MA_c = \sum \left(V_e \times MT_{cv} \times \{1 + SL_f\}\right) \quad (4)$$

$$MA_c = \sum \left(V_e \times MT_d \times MT_{cw} \times \{1 + SL_f\}\right) \quad (5)$$

$$MA_c = \sum \left(A_e \times MT_{ca} \times \{1 + SL_f\}\right) \quad (6)$$

$$MA_c = \sum \left(A_e \times MT_{cu} \times MT_q \times \{1 + SL_f\}\right) \quad (7)$$

Where:

MA_c = material acquisition cost in Brazilian currency (R$);

V_e = volume of the element in m³;

MT_{cv} = material cost in R$/m³;

SL_f = average factor of material loss on site in percentage;

MT_d = density of the material in kg/m³;

MT_{cw} = material cost in R$/kg;

A_e = area of the element in m²;

MT_{ca} = material cost in R$/m²;

MT_{cu} = material cost in R$/units;

MT_q = material quantity in units/m².

3.6.1.3 Construction Activities Costs

Based on the material and category of an element, it is possible to gather from the filled database the necessary input to assemble or build a particular element (e.g. steel column requires a certain number of hours of an assembler as well as a laborer and a welder, each of which has a related cost value per hour). Equations 8 and 9 present the calculation procedure for construction activity related costs.

$$CA_c = \sum\left(V_e \times \sum\{NR_{iuv} \times IP_{cv}\} \times \{1 + SL_f\}\right) \quad (8)$$

$$CA_c = \sum\left(V_e \times MT_d \times \sum\{NR_{iuw} \times IP_{cw}\} \times \{1 + SL_f\}\right) \quad (9)$$

Where:

CA_c = construction activities cost in Brazilian currency (R$);

V_e = volume of element in m³ (may also be area in m²);

NR_{iuv} = number input units required for the activity in hour/m³, m³/m³, hour/m² or m³/m²;

IP_{cv} = cost of input unit in R$/hour/m³ or R$/m³/m³;

SL_f = average factor of material loss on site in percentage;

MT_d = material density in kg/m³;

NR_{iuw} = number of input units required for the activity in hour/kg, hour/m², m³/kg or m³/m²;

IP_{cw} = cost of input unit in R$/hour/kg or R$/m³/kg.

3.6.1.4 Demolition Costs

Following the same line, demolition costs are calculated based on element volumes and/or weights one by one incrementally until all elements have been analyzed, as shown in Equations 10 and 11.

$$DM_c = \sum(V_e \times DE_{cv}) \quad (10)$$

$$DM_c = \sum (V_e \times MT_d \times DE_{cw}) \quad (11)$$

Where:

DM_c = demolition cost in Brazilian currency (R$);

V_e = volume of element in m³;

DE_{cv} = demolition cost in R$/m³;

M_d = material density in kg/m³;

DE_{cw} = demolition cost in R$/kg.

3.6.2 CO_2 Emissions

Carbon dioxide (CO_2) is the dominant gas released by human activities that contributes to global warming. As such, it has been used as the main substance of reference in the reduction of green house gas emissions.

Therefore, emissions of CO_2 gases present an important indicator of environmental impact in the construction industry and can be accounted during the various stages of the life cycle of a facility. Because carbon emissions are estimated as a function of embodied energy. Due to lack of available data, this work only considers production and transportation emission stages of the life cycle emission assessment.

3.6.2.1 CO_2 Emissions during Production

CO_2 emissions during production comprise the processes of extracting and processing the raw material to obtain the desired final product. It also includes chemical reaction related emissions and is calculated here, as presented on Equation 12.

$$EP_{CO2} = \sum \left(V_e \times \frac{MT_d}{1000} \times \{EF_m \times EF_r\} \times \{1 + SL_f\} \right) \quad (12)$$

Where:

EP_{CO2} = emission of CO_2 gases on the production process;

V_e = volume of element in m³;

MT_d = material density in kg/m³;

EF_m = emission factor of manufacturing in tonCO_2/ton;

EF_r = emission factor of chemical reactions in $tonCO_2/ton$;

SL_f = average factor of material loss on site in percentage.

3.6.2.2
CO_2 Emissions due to Transportation

CO_2 emission generated from transportation of materials is an important indicator. It goes beyond just considering material-related emissions and it takes into consideration the distance between the supplier and the construction site. Equation 13 presents the calculation procedure used for this indicator.

$$ET_{CO2} = \sum \left(V_e \times \frac{MT_d}{1000} \times TM_c \times FU_e \times DI_s \times \{1 + SL_f\} \right) \quad (13)$$

Where:

ET_{CO2} = emission of CO_2 gases on the production process;

V_e = volume of element in m^3;

MT_d = material density in kg/m^3;

TM_c = transport modal consumption in L/t/km;

FU_e = fuel emission in $tonCO_2/L$;

DI_s = distance from supplier to site in km, accounted twice to consider the round-trip;

SL_f = average factor of material loss on site in percentage;

The developed database defines an average round trip distance from distributors to a construction site in Rio de Janeiro, Brazil. These values were obtained from Costa (2012). They are used as default distance values, but can be overwritten by the user if he or she creates an attribute named “distance” on the elements.

3.6.3
Thermal Comfort

The concept of thermal comfort refers to the condition in which one is satisfied with the environment’s temperature, and is assessed by a subjective evaluation (ANSI/ASHRAE, 2010). To provide a comfortable environment, engineers and designers need to consider the thermal balance of the building, which according to Riemer (2011) is a principle by which the whole building is considered an entity with a number of energy sources and sinks (where energy goes to). The energy efficiency of a building is defined through its thermal balance.

When comparing building options, heat flow can be used, among others, as an indicator to expose which alternative would need more energy in order to achieve thermal balance. In other words, the option with the highest heat flow would be the one that needs the highest amount of energy and, thus, would be the worse option.

To show that other kinds of indicators can also be incorporated on the process, heat flow on the warehouses was also considered. This indicator only considers the external envelope of the building, i.e. walls and roofs, and according to Lamberts (2016) is calculated as expressed on Equation 14 for walls and on Equation 15 for roofs.

The plug-in first verifies the attribute “IsExternal”, which is a Boolean and only when it returns *true* (meaning the element is on the outside envelope of the building), it follows to calculate the metrics.

$$HF_W = \sum (TT_e \times A_e \times \{T_{ext} + AC_e \times SR_{eo} \times ER_e - T_{int}\}) \tag{14}$$

$$HF_R = \sum (TT_e \times A_e \times \{T_{ext} + AC_e \times SR_{eo} \times ER_e - Fac_r - T_{int}\}) \tag{15}$$

Where:

HF_w = heat flow on walls in Watts;

HF_R = heat flow on roofs in Watts;

T_{ext} = exterior temperature in ºK (consired 303,15ºK);

T_{int} = interior temperature in ºK (considered 298,15ºK);

ER_e = external resistance of the element (based on its material) in m^2K/W;

TT_e = thermal transmittance of the element (based on its material) in $W/(m^2K)$;

Facr = factor applied to roofs representing the fact higher atmosphere layers present low temperatures, forcing horizontal (roof) plans to permanently lose energy through radiation, in ºK (considered ºK according to the standard, based on experimental data)

A_e = area of the element in m^2;

AC_e = absorptance of the element (based on its material) in percentage;

SR_{eo} = solar radiation based on element’s cardinal orientation in W/m^2.

3.7
Decision support

According to Dubravka (2000), Multiple Attribute Decision Making (MADM) deals with the problem of choosing one alternative from a set of alternatives. In order to calculate the choice criterion in the application of most MADM methods, it is necessary to make the attribute values comparable on a common scale. Therefore, values of each attribute are normalized separately. Normalization is the mapping of attributes to the scale [0, 1]. Afterwards, different procedures are applied in order to evaluate each alternative by a single value and choose the best according to the set criterion.

In the developed plug-in, besides presenting the overall absolute calculation results for each model, options are compared based on the principle of multiple criteria decision method. It essentially combines criteria with different units by assigning performance weights to calculate relative score of options. Results present both a macro performance result considering: total costs, CO_2 emissions and heat flow, and a micro performance result in which a weight is designated to each sub-indicator as well. Default weights are shown in Figure 21.

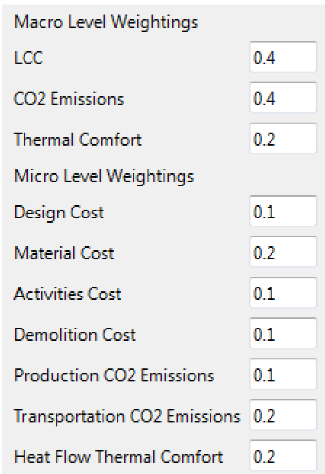

Figure 21: User weightings input window and default values

The system computes relative scores for the various design options being compared based on specified weights and identifies the best performance option by the magnitude of their scores. It employs Multiple Attribute Decision Making (MADM), which is a more suitable option of multi-criteria decision analysis for this work. This is because the method has the advantage of allowing the comparison of attributes with different units of measurement by means of weighting factors.

Also, the number of conceptual design options to be compared will be finite and decisions will be based on information that is not yet finalized or complete. In addition, the method allows trade-offs among attributes as it is envisaged that no single alternative will exhibit preferred value for all attributes (Dubravka, 2000).

Table 11: Normalization procedure options

Type of normalization	Type of attribute	
	Benefit attribute, X^+_j (r_{ij}^+)	Negative attribute, X^-_j (r_{ij}^-)
Simple (SN)	$r_{ij}^S = \frac{x_{ij}}{x_j^*}$	$r_{ij}^S = \frac{x_j^-}{x_{ij}}, x_{ij} > 0$
Njikamp's (NN)	$r_{ij}^N = 1 - \frac{x_j^* - x_{ij}}{x_j^* - x_j^-}$	$r_{ij}^N = 1 - \frac{x_{ij} - x_j^-}{x_j^* - x_j^-}$

Adapted from Dubravka, 2000

Where $x_j^* = \max_i x_{ij}$, and $x_j^- = \min_i x_{ij}$.

Thus, the desirability score for each option is given by Equation 16, where the sum of weights must be equal to 1. It gives the summation of the contribution of each attribute with respect to the cardinal numerical score for each alternative conceptual design solution. The most favorable option will be the solution with the highest desirability score.

$$D_j = \sum_{i=1}^{n} w_i \times r_{ij} \qquad (16)$$

Where:

D_j = desirability score for a particular alternative (max = 1);

n = number of attributes associated with the alternatives;

w_i = weight of attribute or criteria;

r_{ij} = normalized score of the alternative on the particular criteria.

A window displaying results graphically to ease user understanding on which is the best option and the reasons for the choice is then displayed as exemplified on Figure 22. Final results are presented and explained later, in the Results and Discussion chapter.

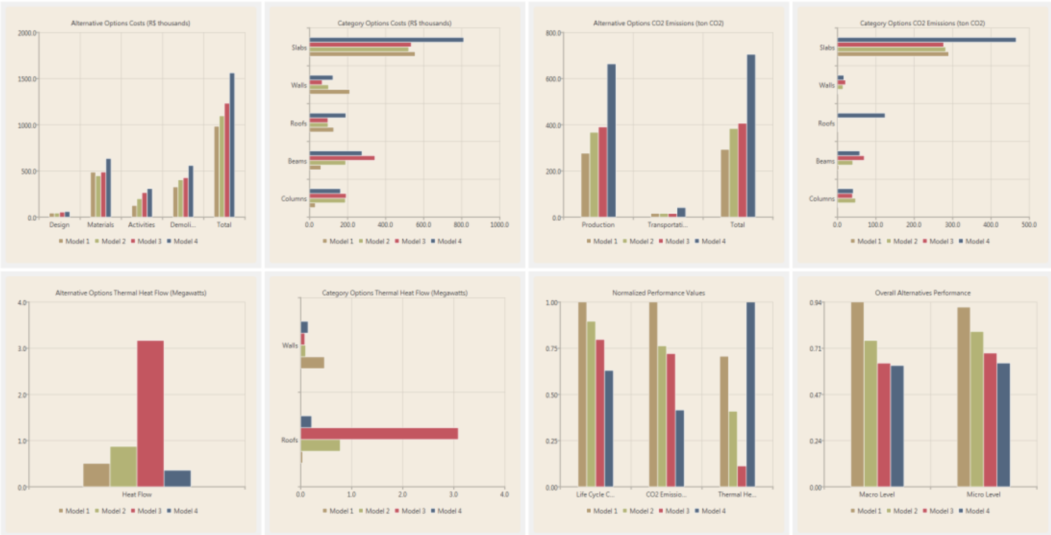

Figure 22: Graphical display of results

3.8 Implementation

The plug-in was developed using the C++ language, one of the most widely adopted commercial programming languages, which is widely used in Academia due to its good performance and the large user base.

The session begins when the “Indicators” button located in the upper tab is clicked. It then opens a new dock window named “Decision Support”, which is composed of four other buttons as depicted on Figure 23 to be further explained.

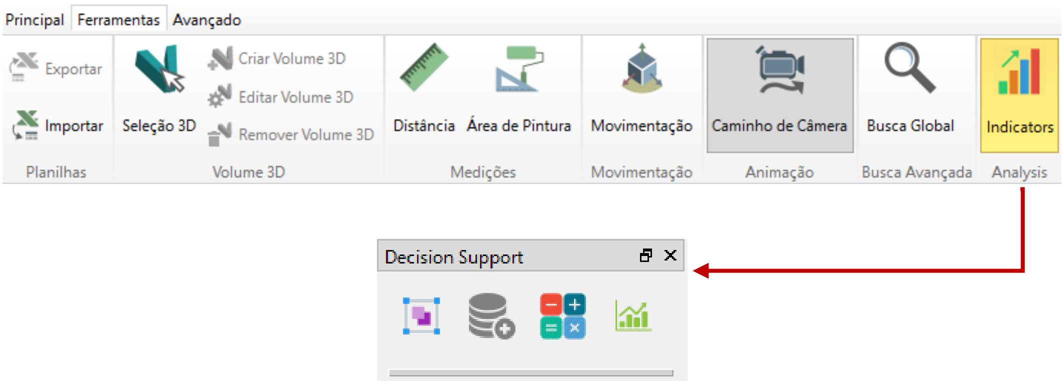

Figure 23: Buttons responsible for initiating the plug-in and its functions

The first button is responsible for going through each element of a model, reading the element's "Family" attribute to identify to which family group it belongs: Column, Beam, Roof, Wall or Slab, while at the same time recognizing which model each element is part of. Depending on which of these categories the element falls into, certain types of data are collected and organized into a "Struct", which is then organized in their corresponding vector with the size of the number of elements in that category as exemplified in Figure 24.

When the process is complete, all elements of all models loaded on the system have been recognized and its parenthood, category and most relevant features gathered and stored in designated vectors accordingly.

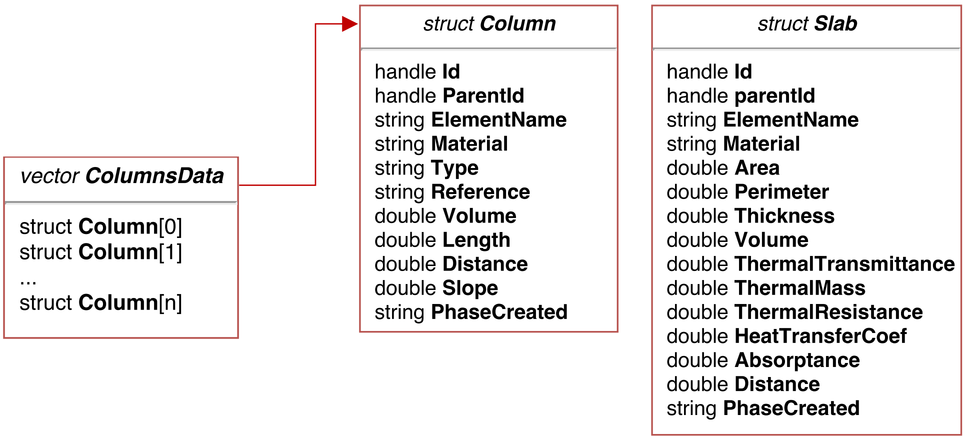

Figure 24: Vector of elements and structures of element's data

After this process is complete, its time to import the database, which is responsible for providing specific data for each type of material. The second button in the "Decision Support" box calls a function that opens a dialog for the user to select the .xls (*Microsoft Excel*) file database he or she wishes to import. The choice for enabling user imports instead of embedding all the data in the code was to allow easier increments of data for new indicators to be calculated and to guarantee up-to-date data which may vary from region to region as well as from time to time.

Upon choosing the desired database, the plug-in goes through each sheet of the file and reads and stores each row's columns data in the corresponding *struct* as presented on Figure 25, then each *struct* is arranged in a vector as exemplified on Figure 26, making sure the whole database is read.

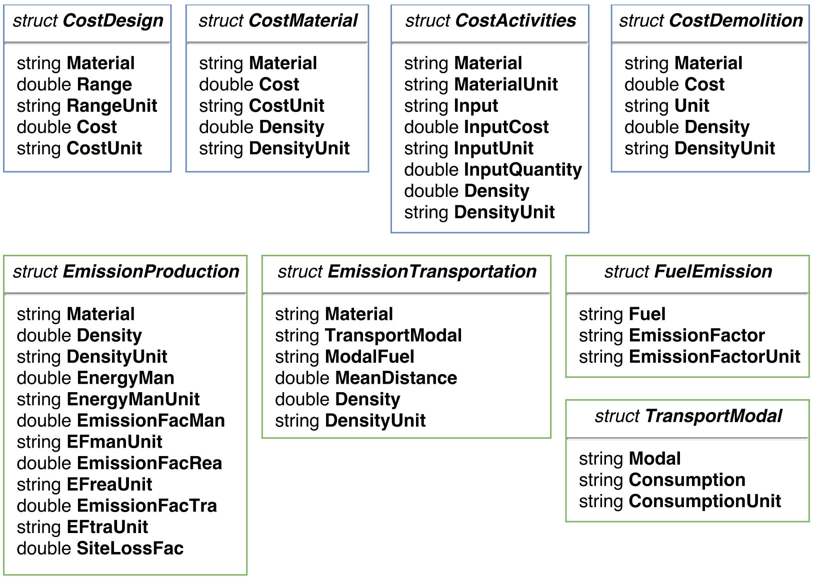

Figure 25: Assembled structures of information for each sheet

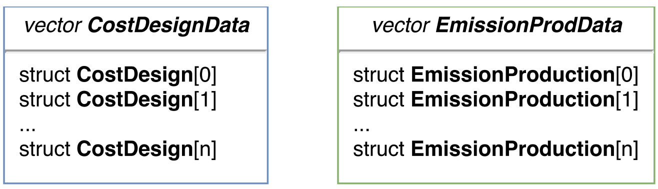

Figure 26: Vector of *structs* from the imported database

Now that information of elements have been gathered and classified, and database information has also been gathered, the calculations presented in section 3.6 can be undertaken.

The calculation procedures are similar: a loop goes through the vector of elements of a certain category (e.g. *ColumnsData*) and for each element gets the material attribute and checks the desired database related vector (e.g. *EmissionProdData)* for the element's material. When the match is detected, and in some cases other conditions are also checked (e.g. verification of IsExternal attribute for roofs and walls to calculate heat flow), the required element data is retrieved from the *struct* information (e.g. Volume) and multiplied by the database material related data (e.g. CO_2 emission factor) to obtain the desired metric for that element.

The calculation process is incremental, meaning that for each category the total value of a certain metric is incremented element by element, allowing elements to have different materials in the same category, as exemplified in Equation 17.

$$EP_{CT} = EP_{CT} + EP_{CE} \tag{17}$$

Where,

EP_{CT} = total material production emissions of columns in tons of CO_2;

EP_{CE} = material production of a single column element in tons of CO_2.

Calculated data of each model is organized on a Model *struct*, which is presented on Figure 27 only for the Walls category and for general model results to avoid repetition, even though it actually contains data from all categories.

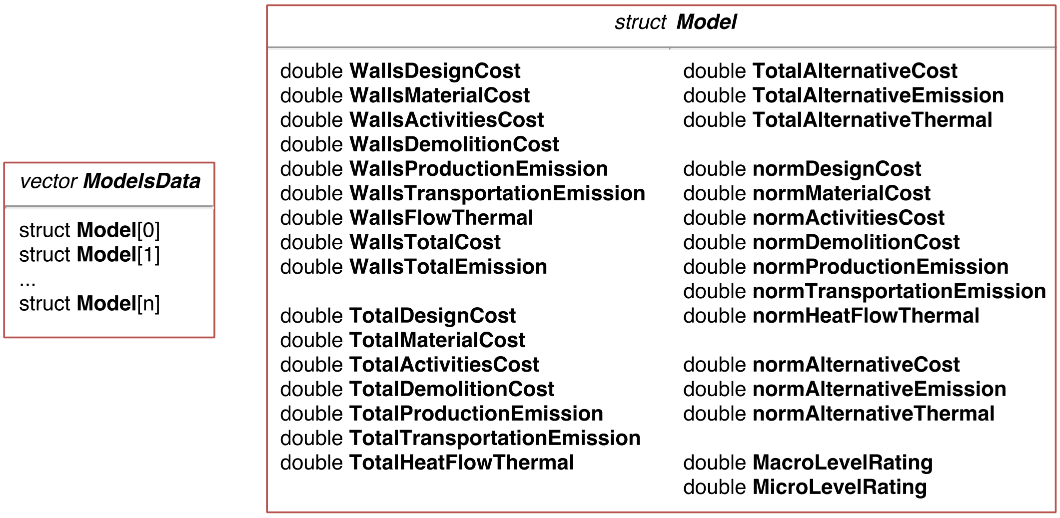

Figure 27: Vector of models and structure of model's data

With the exception of macro and micro level ratings, which depend on user input of weightings to be calculated, all other model attributes are calculated as presented in section 3.6 when the third button is pressed.

The fourth and last button opens a dialog with default values as previously presented in

Figure 21. The user can adequate the weights to his or her needs, ensuring more concern on what he or she values most. When the 'ok' button is pressed, the plug-in verifies if the summation of both micro and macro weights are equal to 1, and if so displays the graphics presented on Section 3.7.

Figure 28 presents the plug-in's overall created and Figure 29 details specific parts of the overall algorithm flow.

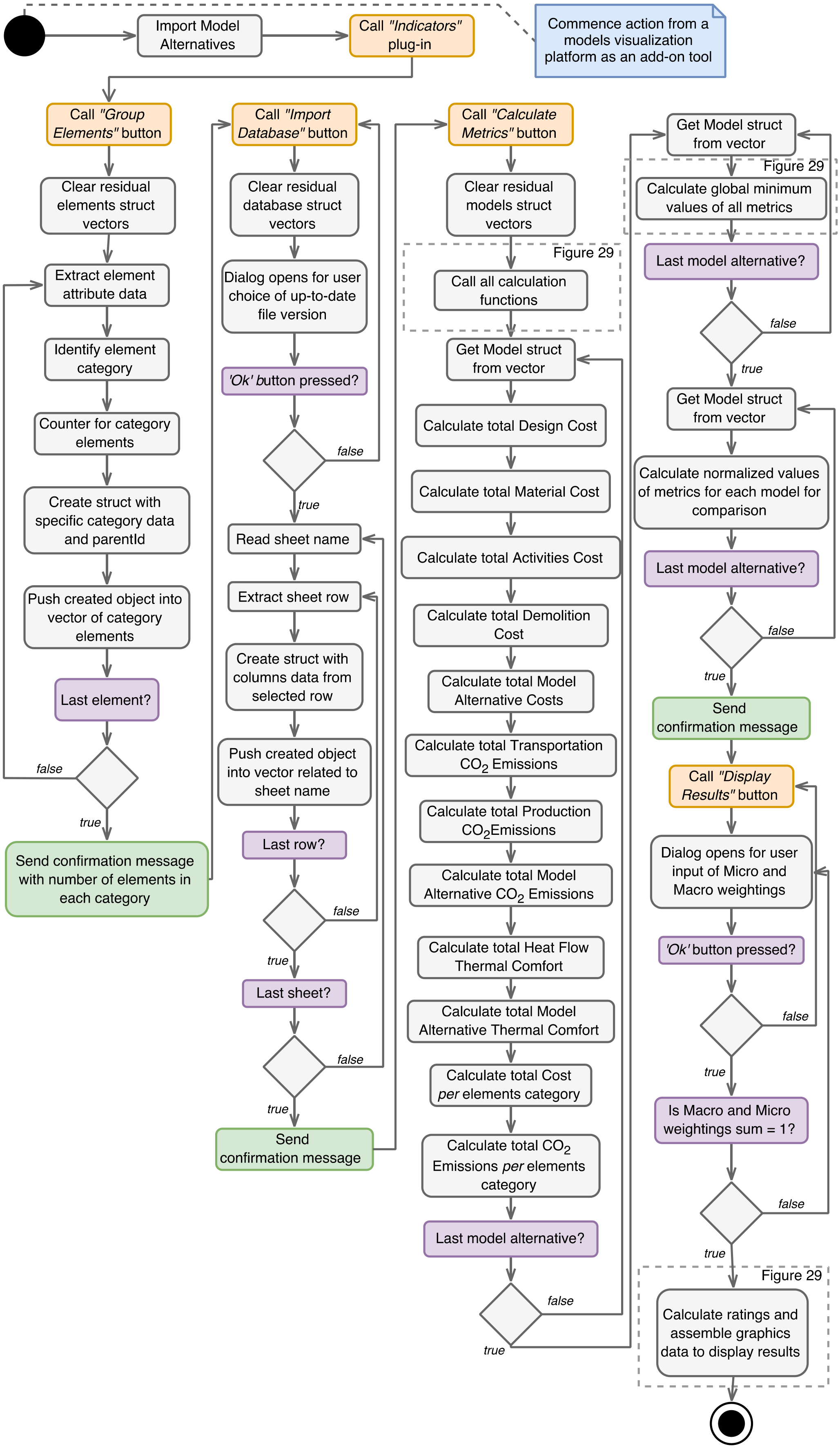

Figure 28: Overall algorithm flow of the designed plug-in

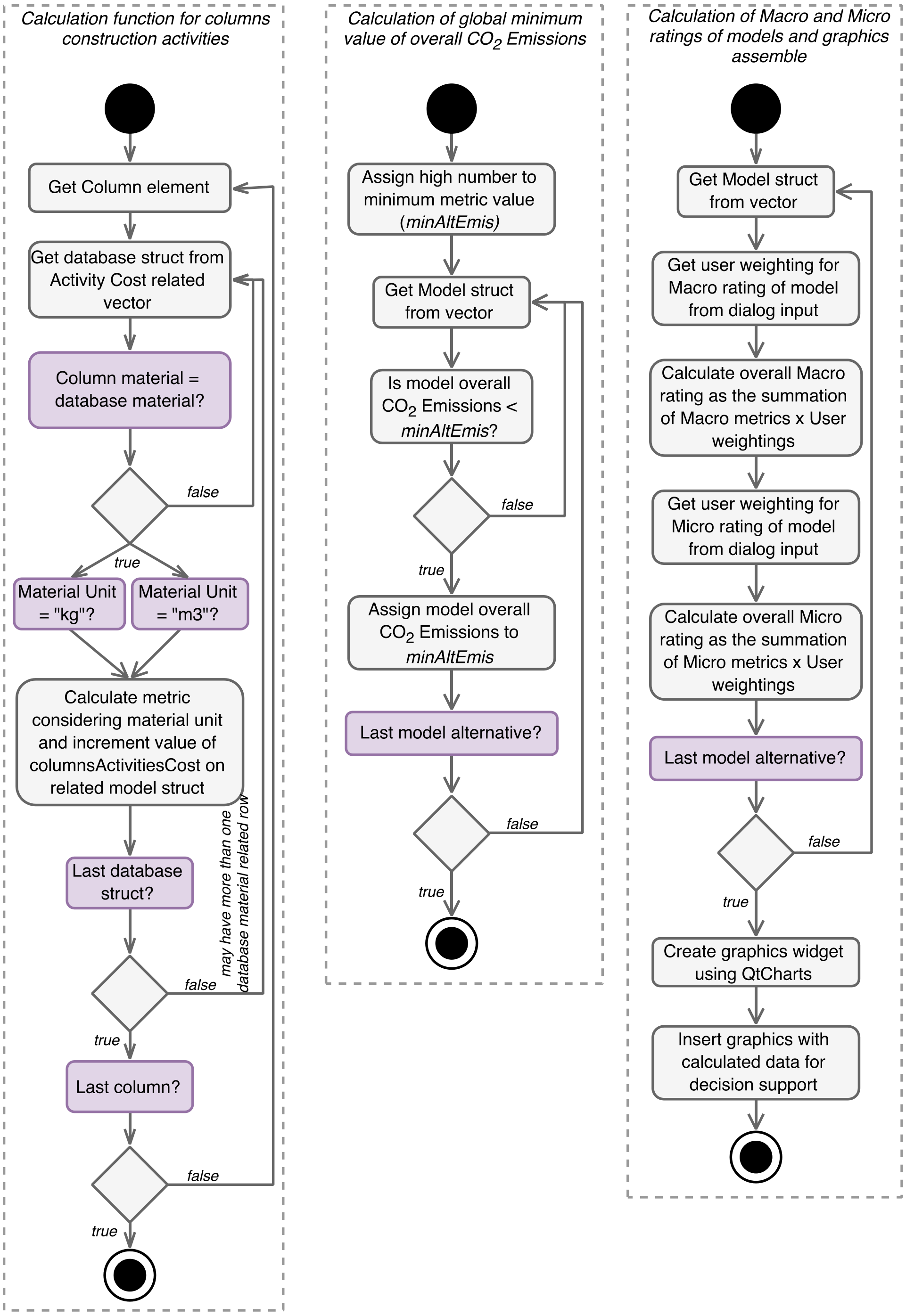

Figure 29: Specific detailing of certain parts of the overall algorithm flow

4
Results and Discussion

To validate the applicability of the developed plug-in, the process was tested on the hypothetical model alternatives described in Section 3.3. After loading the models in the environment and running the required steps, the results were displayed graphically on separate windows.

The first two charts shown in Figure 30 indicate expected costs of each alternative design option (in thousands of R$), with the first displaying results for each stage and the second within each examined category of elements.

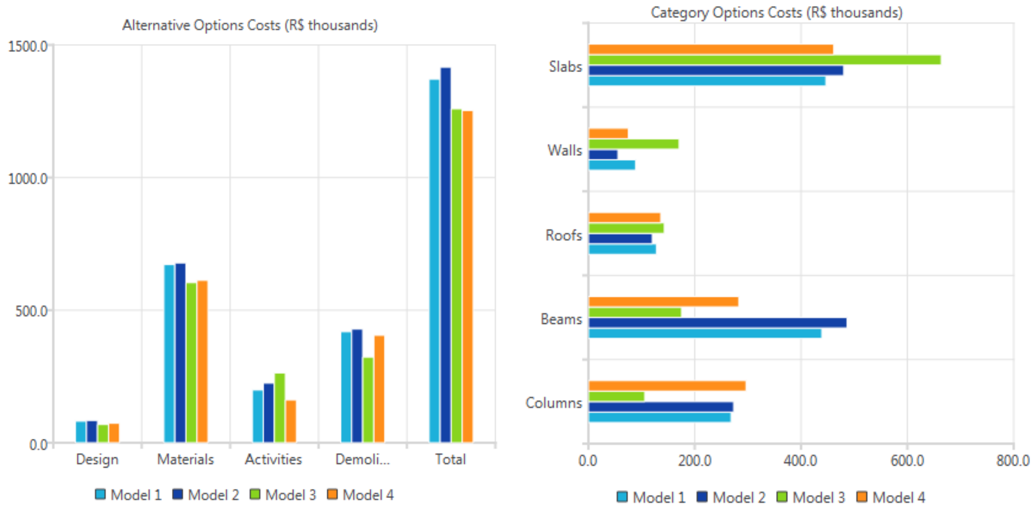

Figure 30: Expected costs of each alternative model (a) *per* stage and (b) *per* category

As can be seen from Figure 30, alternatives 3 and 4 presented expected lower total costs even though when analyzed *per* category model 3 has shown considerably higher costs for slabs and walls. It is interesting to mention that these two design alternatives have considerably lower beam/column costs, which directly influenced total results. This could possibly be explained by the fact that both of them have columns in the middle of the span, a point that was considered within the hypothetical client design scope as a possibility.

Subsequently, the third and fourth charts in Figure 31 show simulated environmental impacts in CO_2 emissions to the atmosphere expected for each of the loaded design alternatives (in tons of CO_2). The third chart displays the overall model emissions due to materials production and transportation to the building site, and the fourth chart breaks down the contributions of each category examined.

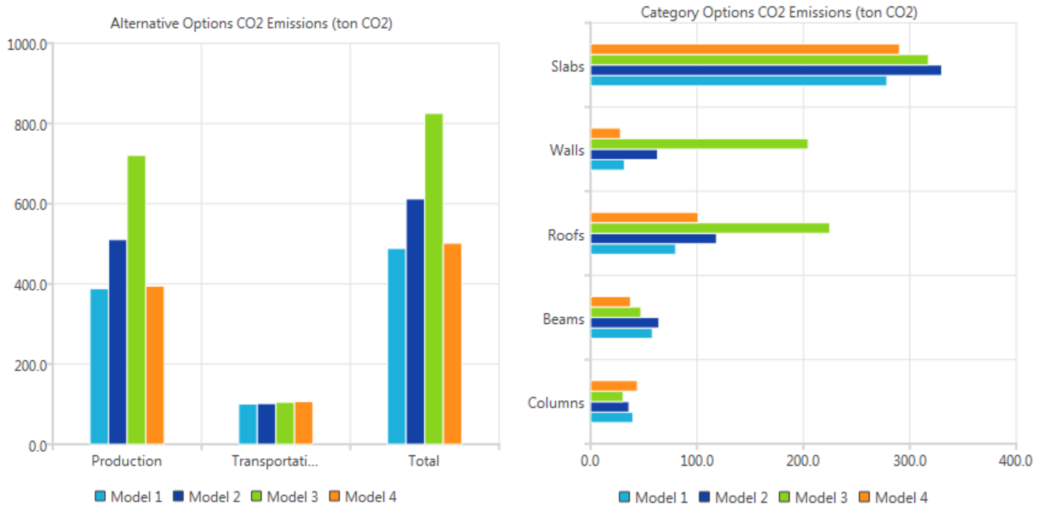

Figure 31: Simulated CO_2 emissions of each alternative model (a) *per* stage and (b) *per* category

Alternative design option 3 presented the highest total level of CO_2 emissions, while options 1 and 4 showed considerably lower overall emissions. This result was directly influenced by the large differences of walls and roofs categories in relation to the other models, which can be observed on the right chart. These results also indicate that, at least for the analyzed scenario, CO_2 emissions due to transportation of materials to site are basically the same among alternatives.

The fifth and sixth charts compare the thermal heat flow simulated for each design option (in Megawatts) and for each category, respectively. Only walls and roofs were considered, since only the envelope of the building influences these results, which are exhibited on Figure 32.

Model 2 clearly displayed a large discrepance in terms of the heat flow that goes into the building when compared to the other models. This could be explained by the choice of material used on the roof, which was aluminum, a great thermal conductor. On the other hand, the roof on model 3 presented the best performance, which confirms the importance of using thermoacoustic tiles. Even so, model 3 did not present the overall best heat flow performance because its walls are partly made of metallic materials.

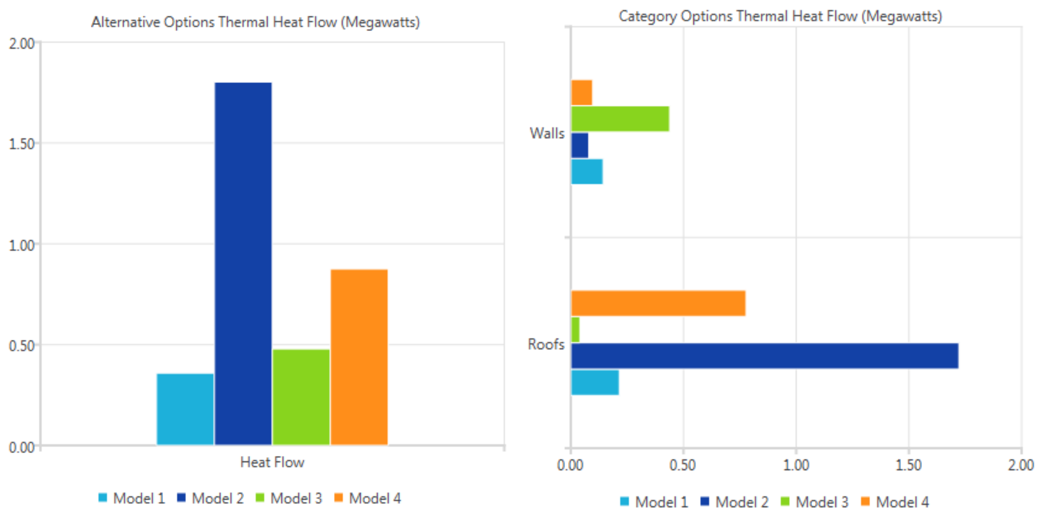

Figure 32: Simulated heat flow on each alternative model (a) overall and (b) *per* category

The two final charts summarize and display the overall performance of each model based on the considered indicators and weights input by users using the multiple attribute decision method described in section 3.7. Figure 33Figure 33 presents normalized performance values of each macro indicator and the overall alternatives performance considering default micro and macro weights, as previously presented on Figure 21.

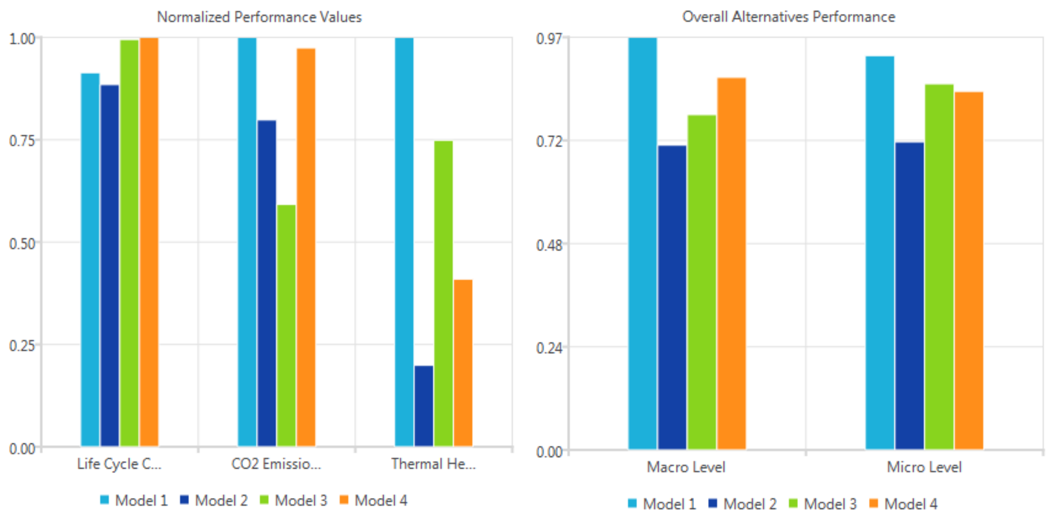

Figure 33: Calculated (a) normalized performance values and (b) overall alternatives performance considering default weightings

An analysis of Figure 33 indicates that larger performance differences among models can be visualized on CO_2 emissions and thermal heat flow, while not so discrepant results can be seen on costs of design options. A final result from the conducted analysis points to model 1 as the overall best design option within the hypothetical scenario.

It is interesting to observe that the final result is greatly influenced by the user's perspective of value generation, which must be agreed between stakeholders. If, for instance, a user defines other indicator weights, the overall best performance design option may change, as in the case displayed on Figure 34, in which the best option shifts to model 4.

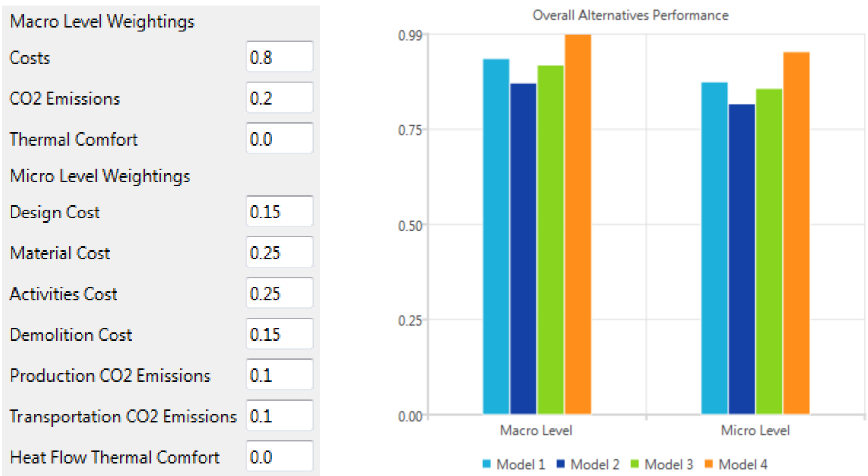

Figure 34: Simulation of different user inputs of weightings and the shift in best design solution

Graphical report of simulation results makes it much easier for the user to understand and identify what element categories, spatial arrangements and types of materials are influencing most each calculated indicator, thus enabling the user to design a new model concept gathering the best aspects of each alternative to achieve an even better solution.

Lean principles can be observed on the capability and impact of user input of weightings to determine the perspective of stakeholders on what generates more value to the project. It can also be explored by combining the best aspects of each model (e.g. roofs of model 3 and walls of model 2) to generate a new "optimized" alternative, thus ensuring continuous improvement of the project process.

Results were very satisfactory to support the assumption that an automated process to analyze design alternatives early on during the design process is a very important line of research and development for the construction industry.

On the other hand, the lack and difficulty to find and structure data to feed the assembled database makes it unclear on whether the obtained results are reliable. Some of the data could only be found in reliable sources from other countries, while others were gathered from not so trustworthy internet sources.

Even when found on reliable sources, most of the information gathered was on *pdf* files. To support this type of automation in the construction industry, governments, companies and suppliers need to partner and develop more structured and enriched databases with standardized materials to avoid duplicity and conflicting information. Only then results from the developed system, or similar, will be robust and reliable enough.

As observed by Oti and Tizani (2015), limitations also exist on issues pertaining data used in the assessment of building sustainability. Systems that generate life cycle process of materials are based on different criteria such as boundary conditions and often produce conflicting analysis results. Even with the availability of secondary data from existing databases, information is not yet comprehensive enough to cover numerous materials comprising the building artefact. One advantage of the proposed work in this aspect is that instead of only observing absolute indicator results, it focuses on the relative comparison among alternatives, which in turn makes the effect of uncertainties in the data less important.

An integration with Geographical Information Systems (GIS) would prove to be very important to automate coordinate dependent indicators such as thermal heat flow and CO_2 emissions due to transportation of materials from fabrication to construction site, which in the presented study needed to be input manually.

From this research, it also became clear, as previously reported in the literature, that IFC interoperable file formats are viable, but still lack information to support better and more automated sustainability assessments.

Finally, it is important to mention the scalability of the proposed plug-in. As the industry shifts to a BIM-based process of project development, the plug-in can be augmented to support innumerous indicators and different categories of elements. As more features are analyzed it becomes increasingly necessary to automate this stage.

The proposed idea could also be expanded to incorporate indicators of green building certification programs such as LEED, making it easier for designers to understand how their decisions are impacting the goal towards a certain certificate, even though these would require more reliable data, since they are based on absolute benchmarks.

5
Conclusion

This work performs a structured research in the literature for each pairwise combination of the three concepts studied. It reported findings for each of these combinations. This way, it showed that a strong relationship between these fields exist on construction related activities. From the knowledge obtained in the literature research, an interrelationship matrix incorporating BIM, lean and sustainability dimensions was developed.

Despite the lack of research that explores collectively all three concepts, this work provides understanding that there is clearly a strong synergy between them. 17 hypothetical interactions, mostly on design related activities, but also during construction processes were identified, as presented on Table 9 and explained on Section 3.1.

By analyzing the proposed matrix, it was observed that certain interactions strongly encourage implementation of an indicator based (e.g. Life Cycle Cost (LCC), Life Cycle CO_2 emissions (LCCE), etc) system to support design decision making processes. This can be achieve through analyses of multiple design alternatives by automatically extracting model data for sustainable assessments. It is important to mention the necessity of focusing on the conceptual design 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.

This work is a step forward in the development of such system. Firstly an IFC file importer was created to make sure data was properly attached to model geometries. Then a prototype BIM plug-in was proposed, implemented and tested on hypothetical models considering the aspects that could be observed from BIM-Lean-Green principles interactions. The plug-in reads, gathers and organizes an imported external database and data from elements of the different alternative design options. From that, it calculates costs, CO_2 emission and thermal heat flow indicators. Finally, it determines normalized performance ratings and displays results graphically to support decision making of designers considering which aspects they value most.

With the achieved results, it becomes safe to say that an integration of BIM and lean principles to support sustainable development in the construction industry is not only possible but necessary. Demonstrated results indicate that a plug-in as the one developed here could prove to be a great asset to support the decision making process of design alternatives or even to understand the impact of design changes.

Based on the knowledge acquired, the following are recommendations for future research in this area:

- Further improve and explore interrelationships, looking between BIM-lean-green for practical evidences to incrementally validate the framework;

- study new indicators to incrementally add to the proposed plug-in, thus making it increasingly more reliable and robust;

- create structured and more reliable data sources to make indicator based sustainable assessments increasingly more feasible and integrate with GIS systems to automate geographical coordinate dependent indicators;

- implement indicators based on guidelines of green building certificates to allow designers to understand the impact their changes might have towards a certain certificate in real-time.

Lean methods and BIM technologies can help organizations and governments to 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, specially the construction industry, an unprecedented opportunity for problem solving around the main sustainable development challenges.

6
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Appendix A – Structural analyses results

PROJETO DE AÇO

CÓDIGO: *ANSI/AISC 360-10 An American National Standard, June 22, 2010*
TIPO DE ANÁLISE: Verificação de membro

GRUPO DE CÓDIGO:
MEMBRO: 2 Column_2 **PONTO:** 3 **COORDENADAS:** x = 0.84 L = 8.00 m

CARGAS:
Caso de carga atuante: 7 COMB1 1*1.25+(2+5)*1.50+6*1.00

MATERIAL:
Steel - Columns Fy = 345.00 MPa Fu = 450.00 MPa E = 210000.00 MPa

PARÂMETROS DA SEÇÃO: W 12x106

d=32.8 cm	Ay=155.84 cm2	Az=50.77 cm2	Ax=201.29 cm2
bf=31.0 cm	Iy=38834.39 cm4	Iz=12528.57 cm4	J=380.02 cm4
tw=1.5 cm	Sy=2370.41 cm3	Sz=808.61 cm3	
tf=2.5 cm	Zy=2687.48 cm3	Zz=1230.67 cm3	

PARÂMETROS DE MEMBRO:

Ly = 9.50 m	Lz = 9.50 m
Ky = 1.00	Kz = 1.00
KLy/ry = 68.40	KLz/rz = 120.42

FORÇAS INTERNAS: **RESISTÊNCIAS DO PROJETO**

Tr = 0.05 kN*m	frvy,mx = 0.32 MPa		
	frvz,mx = 0.20 MPa		
Pr = 133.56 kN		Fic*Pn = 2270.99 kN	
Mry = 235.67 kN*m	Vry = -0.44 kN	Fib*Mny = 834.46 kN*m	Fiv*Vny = 2903.39 kN
Mrz = 1.23 kN*m	Vrz = 50.81 kN	Fib*Mnz = 382.12 kN*m	1.00*Vnz = 1050.89 kN

FATORES DE SEGURANÇA
Fib = 0.90 Fic = 0.90 Fiv = 0.90

ELEMENTOS DE SEÇÃO:
Mesa = Compacto Alma = Compacto

FÓRMULAS DE VERIFICAÇÃO:
Pr/(2*Fic*Pn) + Mry/(Fib*Mny) + Mrz/(Fib*Mnz) = 0.32 < 1.00 LRFD (H1-1b) Verificado
Vry/(Fiv*Vny) + frvy,mx/(0.6*Fiv*Fy) = 0.00 < 1.00 LRFD (G2-1) Verificado
Vrz/(1.00*Vnz) + frvz,mx/(0.6*1.00*Fy) = 0.05 < 1.00 LRFD (G2-1) Verificado
Ky*Ly/ry = 68.40 < (K*L/r),max = 200.00 Kz*Lz/rz = 120.42 < (K*L/r),max = 200.00 ESTÁVEL

DESLOCAMENTOS DE LIMITE

Deflexãos (SISTEMA LOCAL): *Não analisados*

Deslocamentos (SISTEMA GLOBAL):
vxt = 12.9 mm < vxt max = L/300.00 = 31.7 mm Verificado
Caso de carga atuante: 12 COMB6 (1+2+4)*1.00+5*0.70
vyt = 0.1 mm < vyt max = L/250.00 = 38.0 mm Verificado
Caso de carga atuante: 10 COMB4 (1+2)*1.00+5*0.70

Seção OK !!!

Figure A-1: Column calculation verification

PROJETO DE AÇO

CÓDIGO: *ANSI/AISC 360-10 An American National Standard, 2010*
TIPO DE ANÁLISE: Verificação de membro

GRUPO DE CÓDIGO:
MEMBRO: 8 Viga_8 **PONTO:** **COORDENADAS:**

PARÂMETROS DA SEÇÃO: **2 L 4x4x0.5**

ht=0.3 cm	Ay=0.01 cm2	Az=0.01 cm2	Ax=0.03 cm2
bf=0.6 cm	Iy=0.00 cm4	Iz=0.00 cm4	Ix=0.00 cm4
tw=0.0 cm	Wely=0.00 cm3	Welz=0.00 cm3	
tf=0.0 cm	Zy=0.00 cm3	Zz=0.00 cm3	

DESLOCAMENTOS DE LIMITE

Deflexãos (SISTEMA LOCAL):
uyt = 3.3 mm < uyt max = L/240.00 = 63.5 mm Verificado
Caso de carga atuante: 10 COMB4 (1+2)*1.00+5*0.70
uzt = 7.6 mm < uzt max = L/240.00 = 63.5 mm Verificado
Caso de carga atuante: 10 COMB4 (1+2)*1.00+5*0.70

Deslocamentos (SISTEMA GLOBAL): *Não analisados*

Seção OK !!!

Figure A-2: Chord calculation verification

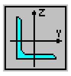
PROJETO DE AÇO

CÓDIGO: *ANSI/AISC 360-10 An American National Standard, June 22, 2010*
TIPO DE ANÁLISE: Verificação de membro

GRUPO DE CÓDIGO:
MEMBRO: 11 Barra simples_11 **PONTO:** 3 **COORDENADAS:**
1.00 L = 1.50 m

CARGAS:
Caso de carga atuante: 7 COMB1 1*1.25+(2+5)*1.50+6*1.00

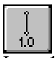
MATERIAL:
Steel (Truss) Fy = 250.00 MPa Fu = 400.00 MPa E = 200000.00 MPa

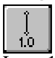


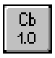
PARÂMETROS DA SEÇÃO: **L 2.5x2.5x0.5**

d=6.3 cm	Ay=8.06 cm2	Az=8.06 cm2	Ax=14.58 cm2
bf=6.3 cm	Iy=50.78 cm4	Iz=50.78 cm4	J=7.83 cm4
tw=1.3 cm	Sy=11.78 cm3	Sz=11.78 cm3	
tf=1.3 cm	Zy=21.14 cm3	Zz=21.14 cm3	

PARÂMETROS DE MEMBRO:







Ly = 1.50 m	Lz = 1.50 m	
Ky = 1.00	Kz = 1.00	Lb = 1.50 m
KLy/ry = 80.38	KLz/rz = 80.38	Cb = 1.00

FORÇAS INTERNAS: **RESISTÊNCIAS DO PROJETO**

Tr = 0.00 kN*m	frvy,mx = 0.40 MPa		
	frvz,mx = 0.40 MPa		
Pr = 18.68 kN		Fic*Pn = 230.59 kN	
Mry = -0.32 kN*m	Vry = -0.36 kN	Fib*Mny = 3.60 kN*m	Fiv*Vny = 108.87 kN
Mrz = 0.43 kN*m	Vrz = -0.40 kN	Fib*Mnz = 3.60 kN*m	Fiv*Vnz = 108.87 kN

FATORES DE SEGURANÇA
Fib = 0.90 Fic = 0.90 Fiv = 0.90

ELEMENTOS DE SEÇÃO:
Mesa = Compacto Alma = Compacto

FÓRMULAS DE VERIFICAÇÃO:
Pr/(2*Fic*Pn) + Mry/(Fib*Mny) + Mrz/(Fib*Mnz) = 0.25 < 1.00 LRFD (H1-1b) Verificado
Vry/(Fiv*Vny) + frvy,mx/(0.6*Fiv*Fy) = 0.01 < 1.00 LRFD (G2-1) Verificado
Vrz/(Fiv*Vnz) + frvz,mx/(0.6*Fiv*Fy) = 0.01 < 1.00 LRFD (G2-1) Verificado
Ky*Ly/ry = 80.38 < (K*L/r),max = 200.00 Kz*Lz/rz = 80.38 < (K*L/r),max = 200.00 ESTÁVEL

Seção OK !!!

Figure A-3: Vertical post calculation verification

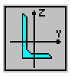
PROJETO DE AÇO

CÓDIGO: *ANSI/AISC 360-10 An American National Standard, June 22, 2010*
TIPO DE ANÁLISE: Verificação de membro

GRUPO DE CÓDIGO:
MEMBRO: 18 Barra simples_18 **PONTO:** 1 **COORDENADAS:**
0.00 L = 0.00 m

CARGAS:
Caso de carga atuante: 7 COMB1 1*1.25+(2+5)*1.50+6*1.00

MATERIAL:
Steel (Truss) Fy = 250.00 MPa Fu = 400.00 MPa E = 200000.00 MPa



PARÂMETROS DA SEÇÃO: **L 3.5x3x0.5**

d=8.9 cm	Ay=9.68 cm2	Az=11.29 cm2	Ax=19.48 cm2
bf=7.6 cm	Iy=143.60 cm4	Iz=96.57 cm4	J=10.82 cm4
tw=1.3 cm	Sy=23.75 cm3	Sz=17.84 cm3	
tf=1.3 cm	Zy=42.77 cm3	Zz=32.28 cm3	

PARÂMETROS DE MEMBRO:

Ly = 2.85 m	Lz = 2.85 m	
Ky = 1.00	Kz = 1.00	Lb = 2.85 m
KLy/ry = 104.93	KLz/rz = 127.96	Cb = 1.00

FORÇAS INTERNAS: **RESISTÊNCIAS DO PROJETO**

Tr = -0.00 kN*m	frvy,mx = 0.23 MPa frvz,mx = 0.23 MPa		
Pr = 139.34 kN		Fic*Pn = 180.76 kN	
Mry = -0.06 kN*m	Vry = 0.08 kN	Fib*Mny = 6.60 kN*m	Fiv*Vny = 130.64 kN
Mrz = 0.22 kN*m	Vrz = 0.22 kN	Fib*Mnz = 5.30 kN*m	Fiv*Vnz = 152.42 kN

FATORES DE SEGURANÇA
Fib = 0.90 Fic = 0.90 Fiv = 0.90

ELEMENTOS DE SEÇÃO:
Mesa = Compacto Alma = Compacto

FÓRMULAS DE VERIFICAÇÃO:
Pr/(Fic*Pn) + 8/9*(Mry/(Fib*Mny) + Mrz/(Fib*Mnz)) = 0.82 < 1.00 LRFD (H1-1a) Verificado
Vry/(Fiv*Vny) + frvy,mx/(0.6*Fiv*Fy) = 0.00 < 1.00 LRFD (G2-1) Verificado
Vrz/(Fiv*Vnz) + frvz,mx/(0.6*Fiv*Fy) = 0.00 < 1.00 LRFD (G2-1) Verificado
Ky*Ly/ry = 104.93 < (K*L/r),max = 200.00 Kz*Lz/rz = 127.96 < (K*L/r),max = 200.00 ESTÁVEL

Seção OK !!!

Figure A-4: Diagonal calculation verification

Appendix B – Developed code

The code developed during the course of this work can be found on www.tecgraf.puc-rio.br/~pedrosf.