INTEGRATE BUILDING INFORMATION MODELING (BIM) AND SUSTAINABLE DESIGN AT THE CONCEPTUAL STAGE OF BUILDING PROJECTS

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To My Parents

ABSTRACT

INTEGRATE BUILDING INFORMATION MODELING (BIM) AND SUSTAINABLE DESIGN AT THE CONCEPTUAL STAGE OF BUILDING PROJECTS

Lately the construction industry has become more interested in designing and constructing environmentally friendly buildings (e.g. sustainable buildings) that can provide both high performance and monetary savings. Analyzing various parameters during sustainable design such as Life Cycle Assessment (LCA) and energy consumption, lighting simulation, green building rating system criteria and associated cost of building components at the conceptual design stage is very useful for designers needing to make decisions related to the selection of optimum design alternatives. Building Information Modeling (BIM) offers designers the ability to assess different design options and to select vital energy strategies and systems at the conceptual stage of proposed buildings.

This thesis describes a methodology to implement sustainable design for proposed buildings at their conceptual stage. The proposed methodology is to be implemented through the design and development of a model that simplifies the process of designing sustainable buildings, evaluating their Environmental Impacts (EI), assessing their operational and embodied energy and listing their potential accumulated certification points in an integrated environment. Therefore, a Decision Support System (DSS) is developed by using Multiple Criteria Decision Making (MCDM) techniques to help design team decides and selects the best type of sustainable building components and design families for proposed projects based on three main criteria (i.e. Environmental, Economical factor «cost efficiency » and Social wellbeing) in an attempt to identify the influence of design variations on the sustainable performance of the whole building.

The DSS outcomes are incorporated in an integrated model capable of guiding users when performing sustainable design for building projects. The proposed methodology contains five modules: 1) Database Management System (DBMS), 2) Energy and lighting analysis, 3) Life Cycle Assessment (LCA), 4) LEED and 5) Life Cycle Cost (LCC). To

improve the workability of the proposed model, a use case of abovementioned modules are going to be created as plug-ins in BIM tool.

The successful implementation of such a methodology represents a significant advancement in the ability to attain sustainable design of a building during the early stages, to evaluate its EI, and to list its potentially earned certification points and associated soft costs.

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List of Abbreviations

AEC	Architecture, Engineering and Construction
AGC	American General Contractors
ANSI	American National Standards Institute
API	Application Programming Interface
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AVI	Audio Video Interleave
AW	Annual Worth
BEPAC	Building and Environmental Performance Assessment Criteria
BIM	Building Information Modeling
BMP	BitMap
CAD	Computer-Aided Drafting
CaGBC	Canadian Green Building Council
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency
CIB	Conseil International du Bâtiment
CIC	Computer Integrated Construction
CIS/2	CIMSteel Integration Standards
CSI	Construction Specification Institutes (CSI)
DBMS	Data Base Management System
DXF	Drawing eXchange Format
DWG	Drawing
EA	Energy & Atmosphere
EI	Environmental Impact

GBCI	Green Building Certification Institute
GDL	Geometric Description Language
GSA	General Services Administration
IAI	International Alliance for Interoperability
IE	Impact Estimator
IAQ	Indoor Air Quality
ID	Innovation in Design
IDD	Input Data Dictionary
IDF	Input Data File
IDM	Information Delivery Manuals
IEQ	Indoor Environmental Quality
IES<VE>	Integrated Environmental Solutions <Virtual Environment>
IFC	Industry Foundation Class
IFD	International Framework for Dictionaries
IGES	Initial Graphics Exchange Specification
ISO	International Organization for Standardization
IUCN	International Union for Conservation of Nature
JPG	Joint Photographic Experts Group
LCA	Life Cycle Analysis
LCI	life cycle inventory
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LCIA	life cycle impact assessment
LEED	Leadership in Energy and Environmental Design
LEED-NC	LEED for New Construction

MADM	Multi Attribute Decision Making
MCDM	Multiple Criteria Decision Making
MODM	multi objective decision making
MEP	Mechanical, Electrical and Plumbing
MR	Material& Resources
NIBS	National Institute of Building Science
NIST	National Institute of Standards and Technology
NPV	Net Present Value
ODBC	Open Database Connectivity
PDF	Portable Document Format
PHP	Hypertext Preprocessor
QT	Quantity Take-off
RFA	Revit Family File
RFI	Requests for Information
RVT	Revit Project File
SAT	Standard ACIS Text
SDNF	Steel Detailing Neutral File
SIR	savings/investments ratio
SKP	Sketch Up Document
SQL	Structured Query Language
SS	sustainable site
STL	Stereo Lithography
STEP	Standard for the Exchange of Product Data
TIF	Tagged Image File
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

USEPA	United States Environmental Protection Agency
USGBC	United States Green Building Council
VNFT	Victorian Native Forest Timbers
VOC	Volatile Organic Compound
VRE	virtual reality environment
VRML	Virtual Reality Modeling Language
WBDG	Whole Building Design Guide
WBS	Work Breakdown Structure
WE	water efficiency
gbXML	Green Building eXtensible Markup Language

CHAPTER 1
INTRODUCTION

1.1. General overview

Studies indicate that lately, the demand for sustainable buildings with minimal environmental impacts is increasing (Biswas et al, 2008). Notably, the construction industry today needs to adopt new approaches for building design to reduce pressures on the environment. An example of these is the green building approach. Incorporating sustainable principles at the conceptual stage is attained by using sustainable design in which designers need to identify associated materials and components based on the selected green building certification system.

Generally, all primary sustainable components and structural materials must perform the following five main functions: 1) Carry prescribed loads; 2) Satisfy serviceability and durability requirements; 3) Be aesthetically pleasing; 4) Be economically practical; and 5) Be environmentally friendly (Somayaji, 2001). In most construction projects, materials are evaluated and selected based on the functional, technical and financial criteria. A clear understanding of the functional criterion of the building materials is essential to ensure the success of a project. It is known that a building project is functionally successful only when its design satisfies the emotional, cognitive, and cultural needs of the people who use it and when it satisfies the technical requisites of the programs it houses (WBDG, 2012).

Technical specifications provide detailed information about the materials used in every component of a building. Usually, such information is provided by the manufacturer and contains information about the type, size and/or dimensions, instalment procedures and other specifications to show the capabilities and the application of each of the material components.

Achieving a cost-effective building requires the evaluation and comparison of all the costs and benefits that will occur over its anticipated economic life. In economic terms, a building design is deemed to be cost-effective if it has a lower life cycle cost, which covers its construction and operating costs. The components of a building’s life cycle cost include the initial design and construction cost, ongoing operations and maintenance costs, parts replacement, disposal costs or salvage value (WBDG, 2012). In order to meet the requirements of a cost-effective building design, the financial criterion of the selected materials should be taken into consideration.

The environmental impact of construction materials is gaining priority within the process by which they are selected. Technically, construction materials should satisfy strength, serviceability, and architectural requirements without negatively impacting the environment (Somayaji, 2001).

Important decisions related to the design of sustainable buildings are made at the conceptual stage of their lives. At the early design stages, usually only conceptual sketches and schematics are available, often rough and incomplete. Still at the early stages of design the most important decisions have to be taken. During the design process more and more information about the problem and the solution will become available, while the flexibility to make decisions in the solution section will decrease. Decisions taken at the conceptual stage of the design process have a higher effect on the final outcome compared to a decision at the end of the design process, although the early decisions are based on less knowledge about the goals to be reached (Derelöv, 2004). The importance of considering sustainability principles during the design stage meets the need for finding long-term solutions that warrant well-being and minimize the needs for natural resources as land use, biodiversity, water, air, and energy. If a project is well planned and sustainable criteria are included in its early stages, the possibility to reduce negative impacts is greater and the cost of criteria implementation is greatly reduced (Bragança et al., 2014). As Bragança et al. (2014) state, the core indicators of conceptual design aim to predict the building's sustainability performance at conceptual stage, where the data available is scarce. Environmental impacts, energy, and life cycle costs related indicators are considered to be those that have a major influence on sustainability principles and are able to be assessed at conceptual design phase.

Energy analysis is typically performed after the architectural/engineering design and related documents have been produced. Schueter and Thessling (2009) think that this practice does not consider the importance of linking the design and energy analysis processes during early stages and yet it leads to an inefficient way of backtracking to modify the design in order to achieve a set of performance criteria. Sartori and Hestnes (2007) believe that buildings demand energy during their life cycle, both directly and indirectly: directly for their construction through operating, rehabilitation and eventually demolition (operating energy); indirectly through the production and installation of the materials they are made of (embodied energy). Energy efficiency is an important feature in designating building materials as being environmentally friendly. The goal in using energy-efficient materials is to reduce the amount of artificially generated power that must be brought to a building site (Jong et. at., 2010). Generally, building materials consume energy throughout their life cycle starting at the manufacturing stage, passing through that of use and finishing at the deconstruction stage. These stages include raw material extraction, transport, manufacture, assembly, and installation as well as disassembly, deconstruction and decomposition.

Traditionally, the energy analyses of proposed building projects have been conducted toward the end of their design stage. In so doing, the ability to model different building configurations during the early design process to identify energy saving alternatives was typically absent. This was due to the difficulty found in modifying the design specifications and the cost of remodeling the building and energy systems at the end of the design stage.

The architecture, engineering and construction (AEC) industry has been witnessing an increasing demand in Building Information Modeling (BIM) used in parallel with the continuous momentum of the sustainable building movement in the last decade or so. BIM and sustainable building together are able to best address the unprecedented challenges in productivity and sustainability encountered by the AEC industry. Presently, BIM tools have the ability to provide users with an opportunity to explore different energy saving alternatives at the early design stage by avoiding the time-consuming process of re-entering all the building geometry and supporting information necessary for a complete energy analysis.

The impact of BIM on design practice is significant due to the fact that it introduces new processes and new ways of delivering designs and construction and facilities management services. Owners are not only demanding that buildings be designed and delivered on time, cost efficiently and with high quality but also that services beyond design and construction should be provided (Clayton et al., 1999). Based on Kubba (2012) and Becerik-Gerber & Rice (2010) the development of a schematic model is prior to the generation of a detailed building model. It allows the designer to make a more accurate assessment of the proposed scheme and evaluate whether it meets the functional and sustainable requirements set out by the owner and helps increase project performance and overall quality. The advent of BIM along with the emergence of challenging global issues like sustainability and life cycle cost of buildings, necessitates that designers incorporate basic performance analysis from an early design phase. Special quality analysis, energy performance, social impact and environmental performance need to be incorporated into its framework by further developing the concept of virtual space and virtual building (Kam et al., 2004). An integrated BIM system can facilitate collaboration and communication processes between project participants in an early design phase to effectively provide a well performing building during operations (Hungu, 2013). BIM helps owners visualize the spatial organization of the building as well as understand the sequence of construction activities and the project duration (Eastman et al., 2008). Combining sustainable design strategies with BIM has the potential to change traditional design practices and to efficiently produce high-performance design for proposed buildings. BIM can be used to support the design and analysis of a building system at the early design phase, which includes experimental structural analysis, environmental controls, construction method, new materials and systems selection, as well as detailed analysis of the design processes. The use of BIM tools can help owners and designers make sustainability-related decisions that have high impact on the life cycle cost of a proposed building early in its design stage. Furthermore, integrating BIM with Life Cycle Assessment (LCA) tools at that stage can help designers select components and materials that have lower embodied energy.

Since BIM allows for multi-disciplinary information to be superimposed through one model, it creates an opportunity for sustainability measures to be incorporated throughout the design process (Autodesk, 2008). Hardin (2009) established three main areas of sustainable design with a direct relationship to BIM. These areas are: 1) material selection and use; 2) site selection and management; and 3) systems analysis. Kriegel and Nies (2008) indicated that BIM can aid in several aspects of sustainable design: building orientation (which can reduce the cost of the project), building massing (to analyze building form and optimize the building envelope), day lighting analysis, water harvesting (reducing water needs in a building), energy modeling (reducing energy needs and analyzing how renewable energy options can contribute to low energy costs), sustainable materials (reducing material needs and using recycled materials) and site and logistics management (to reduce waste and carbon footprints).

Generally, using BIM tools to design sustainable buildings necessitates the selection of materials and systems so that their environmental impacts (EIs) can be easily evaluated. Thus, to quantify the impacts of the selected materials on the environment, an assessment process has to be applied. The common method employed is LCA, which is a tool used for evaluating environmental concerns (Khasreen et al., 2009). It is because of this that designers must keep the entire life cycle of the building and its associated materials in mind. This will promote sustainable development practices through suitable rating systems by recognizing the projects that implement strategies for better environmental and health performance (USGBC, 2011). This research takes one further step to look at the integration between BIM and sustainability at the conceptual stage of the project, and seeks a truly integrated paradigm of the AEC industry in an era of new challenges in design.

Furthermore, in this proposed integration, designers are able to evaluate the sustainability performance of the building and its associated components in a BIM environment by using various applications which are automatically interrelated in the BIM tool. Using the proposed integrated process at the conceptual design stage of the project enables designers/users to determine the type of materials and building components that best meet their needs, to evaluate building components based on green building certification systems, to evaluate energy analysis and cost efficiently with lower environmental impacts and to print the necessary reports in an easy, quick and convenient way.

1.2. Problem Statement

The national BIM report (NBS, 2012) illustrated some very interesting results concerning the current state, attributes and practices of construction professionals in the UK. Their roles concerning sustainability are green product selection, energy calculations, project assessment and managing corporate sustainability. The survey showed that even if more than 50% acknowledged the importance of all three aspects of sustainability (environmental, economic and social) and followed a sustainability policy, only a very small number of them offer an environmental assessment service. It is apparent that the simplistic sustainability overlay and the BIM overlay that are currently widely adopted need clarification concerning the sub-processes of sustainable design.

Although a lot of research has been done concerning collaborative design and the efficient use of BIM, there is little known about the incorporation of sustainable performance analysis into these processes especially at the conceptual stage of the project. Some recent research studies have resulted in producing conceptual frameworks to test interoperability and capabilities of common simulation tools (Azhar et al., 2008; Azhar et al., 2009a; Azhar et al. 2009b; Moakher et al., 2012; Bazjanac, 2008; Che et al., 2010; Hetherington et al., 2011; Magent et al., 2010). Some BIM related frameworks are also based on green building rating systems (Biswas et al., 2009; Wong et al., 2012; Nofera et al., 2010; Ghosh et al., 2011) and others have created tools that are integrated into building information modelling (Schlueter et al., 2009; Welle et al., 2011; Feng et al., 2012; Huber et al., 2011).

Despite these efforts, there is still no comprehensive and structured process to assist professionals to perform sustainability analysis from the early stages of design and achieve optimum results. In spite of the recent efforts toward sustainability, energy efficiency and its resulting value and corresponding cost savings are not key criteria in the building development process, resulting in loosing opportunities to maximize the use of energy efficient building design and technology options. Energy and performance analysis are typically performed after the architectural design and construction documents have been produced. This lack of integration into the design process leads to an inefficient process of retroactively modifying the design to achieve a set of performance criteria. The importance of incorporating all disciplines from the early stages of design is widely acknowledged and documented (Bouchlaghem et al., 2005). Early decisions are crucial in order to achieve sustainability in the resulting design outcome (Schlueter et al. 2009).

Understanding the criteria of sustainability, especially at the conceptual design stage of a project, is very helpful because it allows users to identify exactly what the green building certification standards require for a particular credit. These are always associated with a nontrivial cost, exacerbating the already tightened budget in today’s market. Previous research has shown that in the North American building industry, for BIM and sustainability integration, most cases looked at the implementation of BIM in the green building certification process, especially Leadership in Energy and Environmental Design (LEED), which has become a thriving business paradigm for promoting sustainability in the AEC industry due to governmental endorsement and the strong marketing of the U.S. Green Building Council (USGBC) as well as the Canada Green Building Council (CaGBC).

According to Eastman et al. (2008), developing a parametric model within the BIM environment is capable of capturing project information and generating documentation. With special care taken on the software side, an enhanced BIM application could potentially resolve what used to be major problems in the delivery of sustainable design (i.e. dealing with the complexity of conducting a full building energy simulation, acoustical analysis, and day lighting design). No researcher has yet looked at the possibility of the design team having access to different types of information such as energy consumption, environmental impacts and embodied energy of every building component, pursued green building rating system points and associated costs all within a BIM environment, while the design process is in progress.

Even though the efficient co-ordination of people, tools and technology can lead to significant benefits in the quality and performance of buildings, there are many challenges to be faced. An integrated design process, interdisciplinary collaboration, complex design analysis, careful material and system optimization are required to solve this problem (Nofera et al. 2010). Although previous studies described several methods and techniques used by designers to select optimum combination of building components, author could not find any research that has been implemented with the focus on integrating BIM concept with a decision Support System (DSS) to simulate alternative situations, as well as ranking the alternatives and select the best ones based on both the owners' strategic preferences and the availability of sustainable materials in the market.

Therefore this research intends to introduce various analytical BIM-based integrations which can be used during the conceptual stage to select optimal design alternatives on the basis of multiple criteria. Life cycle cost technique is applied to evaluate the economic performance of various types of materials and building components. Sustainability concepts are applied to design and to provide healthy, comfortable and productive buildings. Sustainability criteria are evaluated by experts in the AEC industry in North America using relative weights comparison and applying decision making techniques. This can be used as a basis for assisting designers and engineers to obtain subtle knowledge about the application of information technology in sustainable design and pave the way for further improvement.

1.3. Research objectives

Although there are many definitions for green buildings, the basic principles, concepts, and goals remain the same: a balanced economy, a safer environment, and social accountability that would improve current and future quality of life. Due to the negative effect of building products on the environment, green building materials should help accelerate the movement toward green and sustainable construction. Designing an integrated model in a user-friendly environment allows owners and engineers design and animate sustainable buildings in 3D mode easily and efficiently at the conceptual stage and allows them to access various types of information to evaluate the sustainable design.

The main objective of this study is to achieve the following sub-objectives:

• **Objective 1:** Investigate the feasibility of creating fully automated integration environment to do sustainable design by improving the functionalities of BIM tools.

• **Objective 2:** Create and develop an efficient framework for this integration that takes into consideration sustainable design requirements and functionality of BIM tool. To do that, designing a database to store information about sustainable building materials and components as well as their sustainability principles and cost will be essential.

• **Objective 3:** Develop a decision support system (DSS) to assist project teams in their selection of construction materials for new buildings during the feasibility analysis stage based on sustainability principles and the life cycle costing techniques.

• **Objective 4:** Identify the gaps that exist in the integration framework and improve the functionality extensions of various tools by customizing their application programming interface (API), and suggest constructive recommendations.

• **Objective 5:** Develop an integrated BIM - sustainable design model, which automates the process of identifying the required number of potential points that must be accumulated based on the commonly used Green Building rating System in Canada.

This research describes a proposed methodology to implement an automated and integrated platform to do sustainable design for buildings at their conceptual stage. The methodology is implemented through the design and development of a model that simplifies the process of designing sustainable buildings and transferring the design information to energy analysis tools to implement energy and lighting analysis as well as listing the potential certification points that can be earned based on the selected system for sustainability. The methodology incorporates an integrated model capable of guiding users when performing sustainable design for new building projects. It incorporates the following five modules: 1) A Database Management System (DBMS) module, 2) An Energy and lighting analysis module, 3) A Life Cycle Assessment (LCA) module, 4) A LEED accreditation and certification cost module and 5) A Life Cycle Cost (LCC) module. Each of these modules is linked to one or more databases containing necessary data and information. The major task of the model is to collect lists of green products and certified materials and have them linked to the building database in the BIM tool. Creating and linking such a database to BIM tool helps users design and animate sustainable buildings in a BIM environment easily and efficiently at the conceptual stage. Part of this integrated methodology is to develop new plug-ins and customize the existing ones built into the BIM tool in order to assist users to connect their design module with the abovementioned five modules in an efficient and consistent manner.

1.4. Methodology

The workflow implemented in this research is as follows:

1) Do a comprehensive literature review to identify the actual needs, gaps and expectations of the construction industry in relation to adopt the integration between BIM concept and sustainable design.

2) Establish a generic integration framework to set the foundation for a BIM – sustainable design integration model. Then a gap analysis is performed to find out what desirable functionalities are missing in current BIM solutions, especially in the Autodesk Revit and supplemental software applications.

3) Design the BIM – sustainable design integration model, which consists of five modules: (i) a DBMS module, (ii) an energy and lighting analysis module, (iii) a LCA module, (iv) a green building rating system module and (v) a LCC module.

4) Develop a Decision Support System (DSS) to help design teams decide on the selection of appropriate types of sustainable building components and architectural and structural families for proposed building projects based on pre-defined criteria in an attempt to identify the influence of

the design variations on the sustainable performance of the whole building. Yet, to select the building's components that lead to achieve the desired sustainability performance goals by identifying the most sensitive input parameters that influence those goals. Therefore, performing a sensitivity analysis for these input parameters is necessary to find the ones that greatly influence the results under observation. Thus, the three main attributes (variables) that are proposed to be studied in this research are: 1) Environmental criteria, 2) Economic factors (cost efficiency) and 3) Social wellbeing. Using Multiple Criteria Decision Making (MCDM) techniques as a verification tool to help the project team make optimum decisions at the conceptual design stage is one contribution of this research.

5) Verify the integrated model through several interfaces of the abovementioned modules, which will be created as plug-ins into BIM tool and afterwards validate the model by using a real sustainable building projects. Figure 1.1 illustrates the logic of the proposed research workflow.

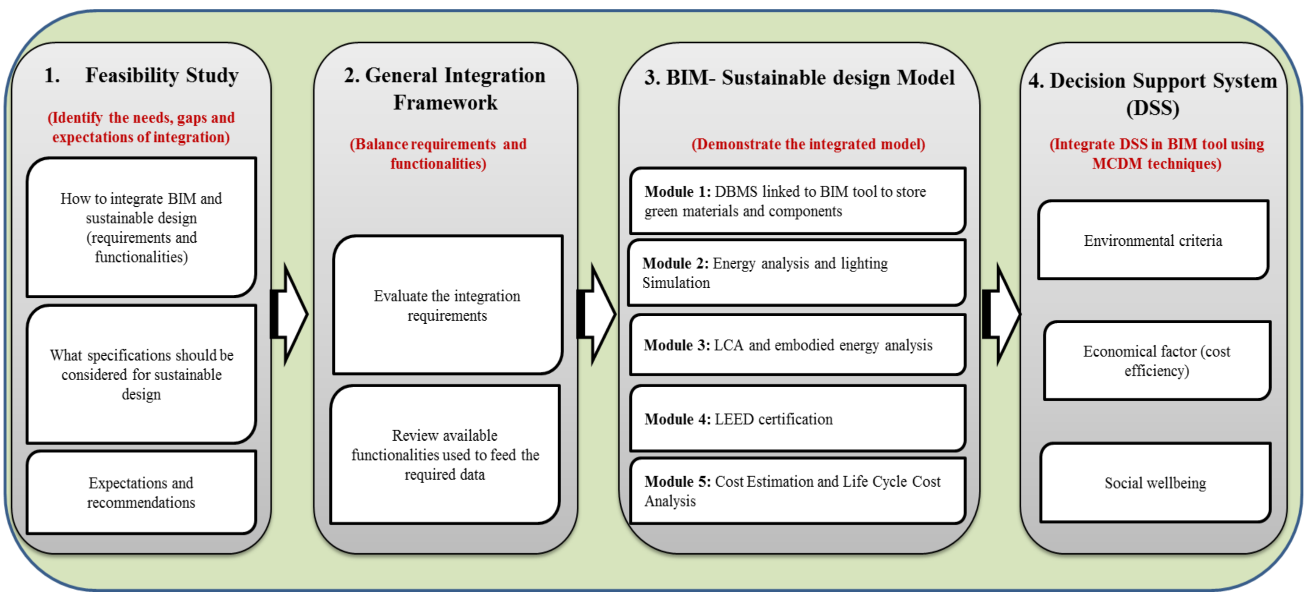

Figure 1. 1. Workflow of the proposed integrated model

1.5. Thesis organization

The thesis is organized through the following chapters:

Chapter 2 is a review of the literature about sustainable design, BIM and decision making techniques of materials' selection. In this chapter different areas and definitions, terminologies, previous works and current practices in BIM are described in detail as well as their connecting potentials with green building works. The chapter presents a comprehensive review of different applications and practices of green and sustainability principles and the application, adoption and implementation of BIM concepts in the construction industry, with a focus on integrating BIM with Database Management Systems (DBMS) to help designers design sustainable buildings at the conceptual stage. This literature review tries to show that one of the most significant aspects of the BIM concept is in sustainable building design. Furthermore, it reviews the different decision-making methods and techniques and looks at their applications in selecting sustainable materials during the design stage. This chapter also reviews the four main divisions of sustainable design (i.e. LCA, Green Building Rating System, Energy analysis and day-lighting simulation and LCC) and their tools as well as it shows how BIM will help the project team in controlling costs. The possibilities of integration with BIM are taken into consideration by reviewing previous research studies that evaluated and compared the capabilities of different tools used in the construction industry for that purpose. It then explains the use of Cost Estimating in BIM, as well as represents the fundamental knowledge related to Life Cycle Cost (LCC) and looks at that studies that have been conducted in relation to that context. Interoperability capabilities of BIM with LCC are also discussed.

Chapter 3 describes the proposed methodology that can be used to implement the integrated BIM model. The methodology automates the integration process by customizing and using BIM tool to enable users connect their design models with different modules within the BIM design tool.

Chapter 4 Includes a technical paper, which presents a methodology that integrates BIM and LCA tools with a database for designing sustainable building projects. The goal of this model is to simplify the process of creating sustainable designs and to evaluate the environmental impacts (EI) of newly designed buildings at the conceptual stage of their life.

Chapter 5 Technical paper II aimed to propose an integrated methodology that links BIM and energy analysis tools with green building certification systems. This methodology will be applied at the early design stage of a project’s life. It will help designers measure and identify potential loss or gain of energy for different design alternatives and calculate the potential LEED points they may accumulate and gain and accordingly select the best one.

Chapter 6 The novelty in technical paper III is to propose a fully automated model that links BIM, LCA, energy analysis and lighting simulation tools with green building certification systems. The implementation of this automation is occurred by developing plug-ins on BIM tool capable of measuring the Environmental Impacts (EI) and embodied energy of every building component used in the BIM model. Using this method, designers will be able to detect and evaluate the sustainability of the proposed building based on Leadership in Energy and Environmental Design (LEED) rating system so that they can modify their sustainable conceptual design in a more efficient way.

Chapter 7 Technical paper IV describes a methodology that integrates BIM with the Canadian green building certification system (LEED©) in Canada, and it explains how this integration would assist project teams in making sustainability related decisions while accumulating the required number of points with regard to the applied green building rating system. The methodology depicts the implementation of a model that automatically calculates the compiled number of LEED certification points and related registration costs for green and certified materials used in designing sustainable buildings all within the application of BIM concept.

Chapter 8 The main purpose of this technical paper V is to propose a methodology that integrates BIM with decision-making problem-solving approaches (i.e. Entropy-TOPSIS) in order to efficiently optimize the selection of sustainable building components at the conceptual design stage of building projects. This paper aims at exposing the feasibility of using BIM for analysing the life cycle costs of sustainable buildings at the conceptual stage. The design alternatives suggested by the DSS are going to be evaluated in an integrated environment that joins BIM concept and Life Cycle Cost (LCC) method to analyze the operational cost of the whole building.

Chapter 9 (Conclusion, Limitations and Recommendations) includes an overview of the developed model based on its several integrated modules included in this research. The chapter also describes the research contributions and limitations and it lists the proposed recommendations for further enhancements and future expansions for the research.

Chapter 10 lists all the references used in the literature review and methodology chapters.

CHAPTER 2

LITERATURE REVIEW

Sustainable design specifications, Building Information Modeling (BIM) and Sustainability Modules to Select Green Building Components

2.1. Introduction

"Going green" is a term very often used based on specific aspects related to sustainability. "Green" can be used interchangeably with sustainability and while also being used to denote reduced demands on natural resources. Architects, environmentalists and designers have recently shed more light on green building designs because green design and sustainability are considered a top priority in environmental buildings. Incorporating sustainable principles at the conceptual stage is attained by using sustainable design wherein designers need to identify associated materials and components based on the selected green building certification system. BIM for instance, is a revolutionary technology that helps engineers design virtual models of a digitally constructed building. This allows owners to visualize the building before it is built. Since BIM allows for multi-disciplinary information to be superimposed through one model, it creates an opportunity for sustainability measures to be incorporated throughout the design process. These measures are building orientation (to reduce the cost of the project), building massing (to analyze building form and optimize the building envelope), day lighting analysis and simulation, water harvesting (to reduce water needs in a building), energy modeling (to reduce energy needs and analyzing how renewable energy options can contribute to low energy costs), sustainable materials (to reduce material needs and using recycled materials) and site and logistics management (to reduce waste and carbon footprints). Generally, using BIM tools to design sustainable buildings necessitates the selection of materials and systems so that their environmental impacts (EIs) can be easily evaluated.

The variety of project boundaries, decision-maker preferences, and the availability of sustainable materials make the decision-making process more difficult in terms of sustainable development purposes when designing sustainable buildings. While, owners want to use sustainable products in their proposed building projects, a decision on the ideal ones can be questioned especially when suppliers offer diverse types of green materials.

The Multiple Criteria Decision Making (MCDM) approach is a well-known branch of the decision-making process. It deals with decision problems under the presence of a number of decision criteria, where a decision-maker needs to choose from either the quantifiable or the non-quantifiable or the multiple criteria. Usually, sustainability objectives are conflicting due to their dependency on each other and therefore, the solution is highly dependent on the decision maker's preferences, which is mostly a compromise. Generally, two different methods are used to solve the MCDM problems, those are: the Multiple Objective Decision Making (MODM) method and the Multiple Attribute Decision Making (MADM) method. MODM deals with many objectives in order to come up with an optimal solution to achieve the set objectives, which sometimes conflict one with another and accordingly makes the goal to attain an ideal solution more challenging and problematic. Whereas in the MADM method the decision maker transacts with alternatives that have variety of performance attributes and factors, which can be either qualitative or quantitative (Shanian and Savadogo, 2006). The MADM method is generally a discrete method, with limited numbers of pre-determined alternatives. It specifies how to process the attribute's information in order to reach an ideal choice. Rao (2007) thinks that this method needs both inter-attributes and intra-attributes comparisons and should involve appropriate explicit trade-offs. To model these attributes, most of the MADM methods are presented through a decision matrix. This matrix consists of: 1) alternatives; 2) criteria; and 3) relative significance of criteria. In this matrix, all the components should be normalized to a comparable scale.

In recent years, with the advancement of technology, applying MCDM methods has become considerably simpler for decision makers and users who are involved in complicated mathematical problems and multiple alternatives. Thus, Decision Support Systems (DSS) are generated to assist in the problem-solving process by combining quantitative data and qualitative knowledge/perceptions; processing information in order to present, compare, and rank potential alternatives; and, ultimately, selecting the one that meets the established decision criteria (Lu, 2007). Besides considering the decision-maker (DM) priorities and preferences, the development of a Decision Support System (DSS) can also help DM in financial/non-financial constraints and objectives (Lu, 2007). DSS can improve decision makers' efficiency, productivity and effectiveness. It can also facilitate the communication between different parties in an organization and contribute to a quick problem solving.

The early design and preconstruction phases of a building are the most critical times to make decisions related to its sustainability features (Azhar et al., 2009). The concentration of designers when doing sustainable design is on the ability to evaluate the Environmental Impact (EI) of the selected products using available methods and tools. The idea of Life Cycle Assessment (LCA) has emerged as the collection and evaluation of the inputs, outputs and the potential EI of a product throughout its life cycle (Guinée et al., 2011). While LCA can be used to assess the sustainability of the built environment, its technique provides comprehensive coverage of the product's EI, therefore it is very useful to apply it at the conceptual design stage of building projects. At that stage the designer must be able to acquire, store, and organize LCA data for the components such that it can be used to generate feedback during the design process (Ries and Mahdavi, 2001). Traditional computer-aided design (CAD) usually lacks the capability to perform sustainability analyses at the early design development while BIM represents both the graphical and non-graphical aspects of a building (Eastman et al., 2008). It takes a multi-dimensional approach, allowing the building team to see how the pieces of their project fit together in real time (McFarlane, 2008). Objects in BIM models not only serve as physical placeholder but also represent a set of information attached to all the necessary data such as supplier information and maintenance procedures (Thomson & Miner, 2006). The combination of sustainable design strategies and BIM technology has the potential to change the traditional design practices and to efficiently produce a high performance design.

Energy analysis is typically performed after the architectural/engineering design and related documents have been produced. This practice does not consider the integration between the design and energy analysis processes during early stages and leads to an inefficient way of backtracking to modify the design in order to achieve a set of performance criteria (Schueter and Thessling, 2008). The total life cycle energy of a building includes both embodied energy and operating energy (Crowther, 1999). Embodied energy is sequestered in building materials during all processes of production, on-site construction, and the final demolition and disposal. Operating energy is expended in maintaining the inside environment through processes such as heating and cooling, lighting and operating appliances.

It is generally accepted that BIM tools are very beneficial and their key strength resides in their interoperability with other programs. In fact, the interoperability between BIM tools and energy analysis software is limited even though new solutions, such as interoperable file formats, have been developed. Although, designers and industry practitioners are testing new ways that are universally accepted amongst different software packages for data exchange, the results are still in their early stages. Yet, using BIM tools to design sustainable buildings necessitates the selection of materials and systems so that their embodied energy can be easily evaluated. Thus, the common method used to quantify the embodied energy of the selected materials is LCA, which is a concept used to evaluate environmental concerns (Khasreen, 2009). For this purpose, designers can use “The Impact Estimator for Buildings”, which is a stand-alone program that allows users to model their own custom assembly and envelope configurations, and provides them with the flexibility to modify the design of proposed and existing buildings. The Impact Estimator allows users to input energy simulation results and calculate their operating and embodied effects.

Cost estimates are essential procedures to be executed throughout the life of a construction project. The success or failure of a project depends on the level of accuracy of the estimated costs compared to the actual ones. The use of BIM and integrate it with cost enable design team to improve efficiencies and reduce time and costs at the conceptual design stage of the project.

Hence, this chapter presents a comprehensive study of different applications and practices related to green and sustainability criteria, Building Information Modeling (BIM) concept, application, adoption and implementation in the construction industry with the focus on integrating BIM with Database Management System (DBMS) to be used by engineers when designing sustainable buildings at the conceptual stage with the emphasis on their associated materials. This chapter also reviews the different decision-making methods and their applications in selecting sustainable materials. The main focus of this chapter is to evaluate previous studies and methods related to the integration of BIM with sustainable design, including energy analysis and simulation and LCA besides evaluating and comparing the capabilities of tools used to apply these concepts in the construction industry. The advent of BIM technology and its implementation in the design of sustainable building projects has caused professionals to start looking at the integration of BIM and LEED Canada certification system. An enhanced BIM application could potentially resolve problems related to delivering LEED certified projects. Using the proposed research at the conceptual stage of the project helps clients to determine the products that best meet their needs, evaluate them based on their selected environmental rating systems, and generate the necessary documents in an easy, quick and convenient way.

2.2. Building Information Modeling (BIM)

2.2.1. Introduction

The term building information modeling refers to technologies and processes that are used across a construction project network to build and utilize a virtual model of the facility (Taylor and Bernstein, 2009). Building Information Modeling (BIM) can be defined in several ways (Hannon, 2007). The National Institute of Building Sciences (NIBS, 2007) states that "BIM stands for new concepts and practices that are so greatly improved by innovative information technologies and business structures that they will dramatically reduce the multiple forms of waste and inefficiency in the building industry." In the construction industry, a tremendous level of coordination is needed in an environment where the collaboration of a number of organizations is crucial in the duration of one project (Alshawi & Faraj, 2002). According to Taylor and Bernstein (2009), Building Information Modeling (BIM) is "a new industry term referring to parametric three-dimensional computer aided design (CAD) technologies and processes in the architecture, engineering, and construction (AEC) industry." However in addition to 3D, BIM can also include dimensions of 4D or 5D (Krauset al., 2007). 4D means 3D CAD drawings with the added dimension of time and 5D contains a 3D CAD model with the added dimension of time-based costs (Kraus et al., 2007). BIM technologies can lead to major productivity improvements by integrating the work of the construction project network (Taylor & Bernstein, 2009).

A building information model is a digital representation of physical and functional characteristics of a facility. It also provides a shared knowledge resource for information about a facility for the facility owner/operator to use and maintain throughout the life cycle of the facility (NIBS, 2007). However, NIBS notes that the acronym BIM is used in several different ways. BIM can refer to 1) a product (a structured dataset describing a building), 2) an activity (the act of creating a

Building Information Model), or 3) a system (business structures of work and communication that increase quality and efficiency) as illustrated in Figure 2.1.

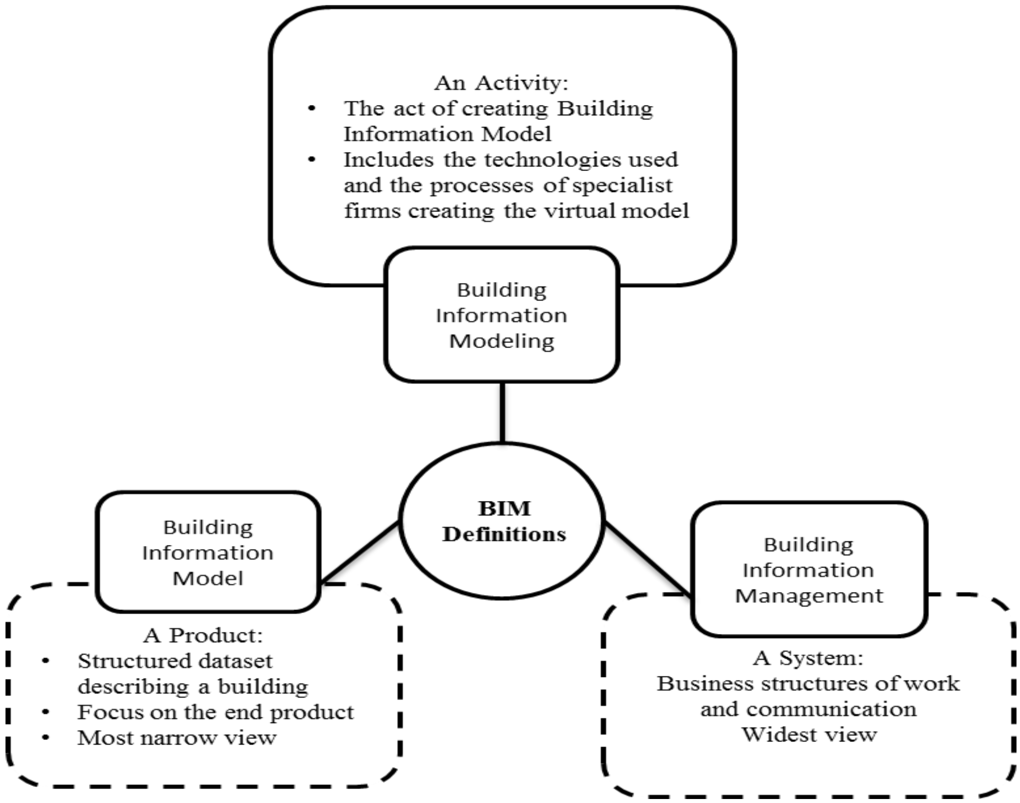

Figure 2.1. Different definitions for BIM (NIBS, 2007)

American General Contractors (AGC, 2006) defines a Building Information Model as “a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users’ needs can be extracted and analyzed to generate information that can be used to make decisions and improve the process of delivering the facility.”

A comprehensive definition of BIM is supplied by the US General Services Administration (GSA), which is:

“Building Information Modeling is the development and uses of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility. The resulting Building

Information Model is a data-rich, object-based, intelligent and parametric digital representation of the facility, from which views appropriate to various users' needs can be extracted and analyzed to generate feedback and improvement of the facility design" (GSA, 2008).

Nowadays, BIM is being used in preconstruction, design visualization, constructability reviews, design coordination, planning of trades and systems, construction scheduling and sequencing (4D), quantity surveys estimating (5D), prefabrication and modularization, and as-built modeling for facilities operations and maintenance (Campbell, 2007). Hence, BIM technologies enable a project network (architects, engineers, contractors and fabricators among others) to collaborate and develop a virtual building (Taylor, 2007). Numerous researchers have reported benefits from the use of BIM, but at the same time many barriers for the diffusion and implementation of this new technology have been recognized (Fox & Hietanen, 2007; Taylor & Levitt, 2007). Furthermore, researchers have identified that the implementation of systemic innovations, such as BIM, influencing multiple firms, are more difficult to implement and diffuse more slowly than localized innovations (Taylor, 2007; Taylor & Levitt, 2007).

Therefore, one can conclude that: 1) BIM is a model-based technology linked with a database of information, 2) It has the ability to automatically coordinate changes made anywhere in the model views or drawing sheets, schedules, sections and plans, 3) BIM increases the ability to control data and information in an interoperable format, 4) It can be used with a variety of programs/functions such as simulations, structural design, cost estimations, energy analysis, scheduling and facilities management.

In the research proposed, BIM is used to emphasize that it couples both the technologies and the advanced methods enabling the creation of a virtual building information model.

2.2.2. The implementation of BIM

The implementation of BIM has been studied especially from the perspective of technological interoperability (e.g. Szykman, Fenves, Keirouz & Shooter, 2001; Halfawy & Froese, 2005; Roy & Kodkani, 1999). This is not surprising since the applications supporting the design process have been created to support separate specialists (architects, structural engineers, etc.), and largely not made to interact with each other (Alshawi & Faraj, 2002). This is why there has been a great need to find ways to integrate the applications, or at least the information they contain. BIM has been preceded by the evolution from paper based drafting to two dimensional (2D) CAD (computer-aided design) and later to three dimensional (3D) CAD geometries (Taylor & Levitt, 2007). The shift from paper-based drafting to 2D CAD has caused numerous changes within organizations including the redistribution of work (Henderson, 1999), the development of completely new tasks (e.g. technical experts), changing skill requirements (Manske & Wolf, 1989; Salzman, 1989) and the creation of new drawing standards (Henderson, 1999). Similar organizational impacts have been seen when shifting from 2D CAD to 3D CAD geometries. The difference between BIM and the earlier experiences with 2D CAD and 3D CAD geometries is that the impact of BIM is an inter-organizational instead of an organizational one. Hence, the use of BIM creates new interdependencies and collaboration requirements among construction project networks (Taylor & Levitt, 2007).

In reference to the cost of adopting BIM, an initial investment is needed for BIM software, hardware, staff and training. Implementing BIM can be costly, but is important to keep in mind the cost savings associated with BIM in the long run. The cost of creating the intelligent Building Information Model is ideally shared between interested parties since everyone benefits from the 3D model. This initial investment is considered to be much less than the cost benefits for all the parties involved in the process.

To justify the additional cost involved with implementing BIM, the production benefits should be assessed. One of the ways is to track the reduction of errors by the lowered number of Requests for Information (RFIs) and Change Orders on a project. Change orders account for 8 to 12 percent of the cost in a typical design project, but design with BIM has proven to reduce the change orders to as little as 2 percent of the construction cost. In large projects, this could be equal to millions of dollars in savings (Kreygiel &Nies, 2008).

The functional and performance capabilities of different BIM solutions are relative and contextual since there is no single platform that will be ideal for all types of projects. Table 2.1 lists some of the most popular solutions (tools) in the current market, according to McGraw-Hill Construction (2009).

This requires the decision-makers to take a renewed investment-based view, instead of the traditional cost-based view, of technology such as BIM.

Table 2. 1. Overview of popular BIM software solutions in current market (Source: Eastman et al. 2008; Smith and Tardif, 2009)

Features	Revit®	Bentley®	Vico®	ArchiCAD®
BIM tool	Authoring; partial auditing and analysis	Authoring; partial auditing and analysis	Authoring; partial auditing and analysis	Authoring
IFC Certified	Yes	Yes	Yes	Yes
Operating System	Windows	Windows	Windows	Windows and Mac OS X
ODBC Support	Yes	Yes	Unknown	Yes
Supported Interfaces	DGN, DWG, DWF, DXF, SAT,SKP, gbXML, AVI, BMP, JPG,TGA, TIF and API	Primavera, STTAD, RAM, DGN, DWG, DXF, PDF, STEP, IGES and STL	Primavera®, MS Project, Revit, Tekla, ArchiCAD, DXF, DWG, PDF, VRML and JPG	CIS/2, SDNF STEP DWG, DXF, VRML, STL, HOOPS, SAT, 3DXML and IGES
Strengths	Market leader, user-friendly, direct link interfaces, excellent object library, multi-user interface and bidirectional drawing support	Almost full AEC modeling tools, support complex curved surfaces, support developing Parametric objects, provide scalable support	Best contractor oriented tool, first real 5-D support, Direct support for Revit, Tekla, Primary and ArchiCAD®. Complete project management.	Oldest tool, intuitive interface, easy to use, large object libraries, rich supporting application, only strong BIM tools for MACs
Weakness	Limitations on parametric rules dealing with angles and does not support complex curved surfaces	Large and non-integrated interface, heterogeneous functional modules include different object behaviors	Complex package of highly Specialized modules, expensive, sharp learning curve.	Limitations on parametric modeling, not supporting update rules between objects and scalability issue

In the North American market, the Autodesk Revit (including Revit Architecture, Structure and MEP) is the most prevailing BIM tool. Revit Architecture is a platform for Building Information Modeling (BIM) with a database and documentation system that helps to design and build project with complete drawings, scheduling, and materials quantity take offs. It also provides extensive detail library, and these details are compatible with the Construction Specification Institutes (CSI) MASTERFORMAT and UNIFORMAT. The main reason that Revit is used in this research proposal as a BIM tool is as follows:

1. **Availability:** Most of the construction industry in North America is using Autodesk products;

2. **Interoperability:** Revit supports various file formats especially IFC and gbXML import/export; it also supports ODBC which enables flexible data extraction;
3. **Extensibility:** Revit has numerous useful plug-ins and extensions available that fit in very well for this study, besides a comprehensive API guide for developers.

2.2.3. The recent practice on BIM

Presently, new Information Technology tool comes to narrow the existing gaps in the constructing industry and specifically buildings and their impact on the environment. BIM and its applications in that industry gained a momentum due to its application in every stage and phase of a project, from design through construction and operation. BIM is a new approach that emerges to design, analyze and document of a building. In fact, BIM, as a revolutionary concept, has been engaged in the entire information management of the design process starting from the conceiving design to the end of the projects' lifecycle. Basically, BIM is an organizing concept that contributes in the lifecycle of a building by creating and managing its related data in a convenient process. Specifically, BIM as new technology uses 3D modeling to increase the productivity of the building design (Holness, 2008).

Goedert and Meadati (2008) consider that BIM is an excellent concept that can deal with data management capability and retrieve information. Unlike the traditional CAD software, BIM technology can replace CAD lines, symbol entities, and dimensions in digital drawings with objects that are smart and digitally documented such as walls, doors, and windows. In addition, these objects consist of document information, specifications, cost and other documents. BIM stores the projects' information in a computerized database. Then it can display them in many other formats. Any information stored inside the database can consist of 2D drawings, 3D geometry, text, spreadsheets, schedules, and calculations. As an advanced technology, BIM covers all buildings components whether it is geometry, geographical information, quantities and spatial relationship. BIM helps to control and mechanize building in the whole lifecycle. In fact, BIM is an open and shared property that can track quantities and materials. However, Building Information Modeling (BIM) technology today is having limited impact on green building process, but it can be enhanced by changing the future design of green building by including valuable tools in the near future. In addition, Smart Market Report (2009) shows that about one-third of the BIM users say it is highly beneficial in delivering buildings with better performance, for example 15% of the users are experiencing a high level of performance with BIM in terms of energy analysis. Based on the previous literature reviews in the preceding paragraphs, there is no single database that consists of green and certified products that can be used in BIM technology tool such as Revit Architecture.

Currently, considerable research is done in the area of green products and Building Information Modeling (BIM) to identify how they can affect the way of designing sustainable buildings. Researchers are working on developing and improving the methods of sustainability and green design through many software and models; there are considerable researches done in terms of energy analysis and materials selection and the ways they affect the life cycle operation of the building.

This research proposal focuses on the methodology used in developing and implementing a full automated model that incorporates database management system to store detailed information about construction green materials and certified products necessary to execute sustainable design at the conceptual stage of a building project based on the US and Canadian Green Building Council (USGBC and CaGBC) certification system. Modeling this process is advantageous particularly when explicit methods and techniques are followed and the pertained parameters are identified.

2.3. Sustainability and green building

The principles of sustainable development define the ecological, economic, social and cultural framework for the activities of communities, enterprises and individual citizens (Häkkinen, 2007). The UNEP's vision (2006) for sustainability in the building and construction sector is as follows:

- buildings are routinely designed and maintained to be optimized over their entire life cycle;
- legislation and building standards include sustainability considerations and requirements;
- environmental aspects are normally considered in any building and construction project and include short term as well as long term aspects;
- policies and incentives provided by the government support sustainable building and construction practices; and

- investors, insurance companies, property developers and buyers/tenants of buildings are aware of sustainability considerations and take an active role in encouraging sustainable building and construction practice.

Charles Kibert (2008) states that sustainability or sustainable development is a foundational principle that covers a variety of efforts to ensure a civilized quality of life for the future generation. The core of sustainability has the following three dimensions: environmental, social and economic. These have been drawn in a variety of ways, as ‘pillars’, as concentric circles, or as interlocking circles as shown in Figure 2.2. The International Union for Conservation of Nature (IUCN) Programme 2005-8, adopted in 2005, used the interlocking circles model to demonstrate that the three objectives need to be better integrated, with an action to balance between the dimensions of sustainability as illustrated in Figure 2.2.

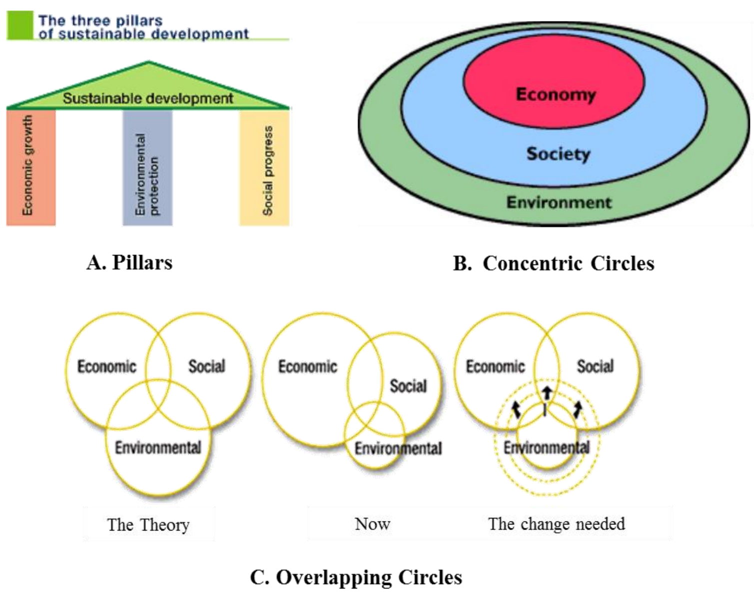

Figure 2.2. Three Visual Representations of Sustainable Development: Pillars, Circles, Interlocking Circles (IUCN, 2006)

The United States Environmental Protection Agency (USEPA) has defined green building as “creating structures and using processes that are environmentally responsible and resource-efficient throughout a building’s life cycle from design to construction, operation, maintenance, renovation and deconstruction. This process expands and complements the classical building design concerns of economy, utility and comfort. Green building is also known as a sustainable or high performance building.” (USEPA, 2009)

Sustainable construction and high performance construction are usually used similarly, however, sustainable construction is much more extensive especially in terms of environmental, social and economic issue. The Conseil International du Bâtiment (CIB) (1994) listed seven principles of sustainable construction which assist professionals during all phases of design, construction and through its entire life cycle. These principles are 1) Reduce resource consumption; 2) Use recyclable resources; 3) Protect nature; 4) Reuse sources; 5) Eliminate toxics; 6) Apply life-cycle costing and 7) Focus on quality. These sustainable construction principles affect the resources needed to design the built environment and to operate it throughout its life cycle including land, materials, energy and ecosystems. The national building science has defined green building materials specifications as shown in figure 2.3.

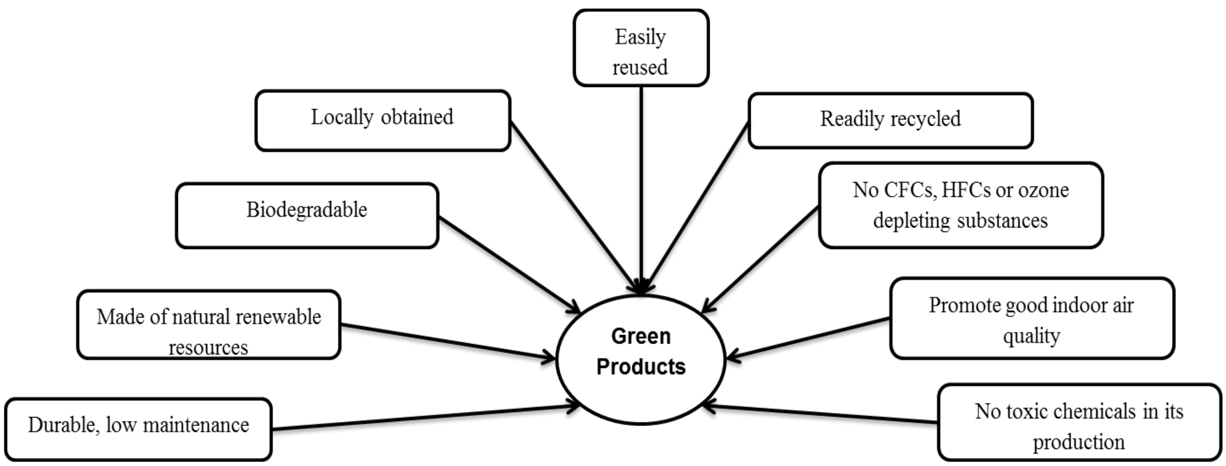

Figure 2.3. Environmental Characteristics of Green Products (NBS, 2009)

According to these characteristics, green buildings will be less harmful to humans and the environment, as opposed to buildings of the traditional type, and they will be more beneficial socially, economically and environmentally.

2.3.1. Sustainability Measurement Tools

The tools used include those that depend entirely on criteria scoring systems. These are rather subjective scoring systems that assign point values to a number of selected parameters on a scale ranging from small to large environmental impact (Assefa et al., 2007). The main principles of sustainability development are to: reuse resources, decrease resource consumption, protect nature, use recycled resources, eliminate toxicity, apply life cycle costing, and focus on quality

(Kibert, 2005; Sinou, 2006). Several environmental tools and methodologies for evaluating the environmental impact and performance of buildings are presently being developed. On a global scale there are some common criteria scoring systems such as SBTool (Sustainable Building Tool), which is an international system that emerged and is coordinated in Canada; LEED (Leadership in Energy and Environment Design), which is a tool developed in the USA with international application, and CASBEE (Comprehensive Assessment System for Building Environmental Efficiency), a technique developed in Japan. In Europe, some of the most commonly used systems include BREEAM (Building Research Establishment Environmental Assessment Method) in the UK, HQE (high environmental quality) developed in France, and the VERDE method developed recently in Spain (Sinou, 2006 and Fowler, 2006).

Two different methods are defined to describe the sustainability performance of sustainable buildings: a single number method or an array of numbers method. The advantage of a single number method is that it is very easy to use, while the array of numbers method provides more detail. The single number approach was adopted in LEED assessment methodologies, while the array method is utilized in SBTool, which uses a relatively large quantity of information to assess the building. The LEED scoring system results in a single number that determines the building's assessment or rating, according to the accumulation of points in various impact categories, which are then totalled to obtain a final score (Mereb, 2008). If a single number is used to score a building, the system has to convert many various units used in measuring its environmental impacts and its resources (water consumption, energy use, materials, waste quantities, land area footprint, and recycled materials) into a series of points that should be calculated to result in a single overall score that on a scale can range from poor to excellent. A building assessment system can also utilize an array of numbers that result from measuring the building's performance in major areas, such as global warming potential, energy consumption, and waste generation; an overall score could then be obtained after weighting the aggregation (Mereb, 2008).

2.4. Using BIM for Sustainable design

When looking into the paradigm shift in the green building movement and the transition to building information modeling, professionals with experience in both areas tend to think about possible interoperability between them. For instance, at the very beginning of the project delivery, the owner and the project team will be able to work on the sustainability assessment. Later on, with all the design information stored in an integrative building information model, the project team will have a reliable data source to facilitate the realization of all sustainability goals in the construction and eventually the operation and maintenance processes. Because of the flexibility of information exchange, the project team can continuously update the BIM model to monitor and manage building performance.

Krygiel and Nies (2008) identify and demonstrate seven strategies for using BIM tools to achieve a “green” approach to building design. These strategies are categorized as belonging to either building form or building systems. The first strategy they identify involves building orientation – how the structure is placed on a site relative to the sun’s path throughout the year. Based on the local climate, a building’s orientation can be used to optimize lighting, ventilation, heating, and cooling. This requires having data such as the location’s latitude, longitude, and solar south. Most BIM tools have the capability to set a project location and identify a true orientation. In addition, these tools typically have the capability to perform lighting assessment on building geometry, so design teams can visualize at what times of the day and year a building (or parts of it) will be in either sun or shade.

The second sustainable design approach involves building massing. This is primarily driven by the building type (i.e. office, residential, school and etc.) and the local climate. The volume and shape of the building can greatly impact lighting, ventilation, heating, and cooling of the project. Through the utilization of the BIM tool and energy analysis software, it can be a quick and efficient process to compare multiple massing configurations in terms of energy consumption. For example, by using Autodesk Revit, it is possible to create parameters to control the ratio of length vs. width vs. height and the total floor area. Then, by exporting the BIM model to an energy analysis tool, a quick comparison can be made between different massing configurations to understand which option will have the optimal performance.

The third strategy related to building form is day lighting optimization. The demand for artificial lighting that contributes to internal heat gain and consequently space conditioning should be reduced if buildings are designed to maximize the use of natural day lighting. Proper day lighting relies on building orientation, massing, and envelope configuration (glazing placement, materials, and construction assemblies).

The fourth strategy under the category of building systems involves the capturing of rainwater, which is known as water harvesting. Similar to optimizing the building form, it depends on understanding the impact of the local climate. By using a BIM model, components (such as roofs) can be quickly accessed from the model's database and exported/imported into a spreadsheet to calculate total water collection potential.

The fifth, and probably the most commonly referenced strategy, is energy modeling and analysis. The optimization of energy performance depends on the previously-discussed strategies such as building orientation, massing, and day lighting. The first step is to identify the project requirements with regard to lighting, heating, cooling, and power needs. Sometimes these goals are based on performance criteria introduced in standards and codes, such as the American Society of Heating, Refrigeration, and Air-Conditioning Engineers 90.1 (ASHRAE 90.1), the LEED Green Building Rating System and others. In an effort to meet project goals, the use of a BIM model can reduce analysis time, thereby allowing the design team to perform more iterations and in-depth optimization studies. The appropriate energy analysis tool(s) will depend on the design stage of a project and the desired output information by the design team. Some of these tools include: Ecotect, Green Building Studio, eQUEST, EnergyPlus, and IES. It is important to note that most analysis and optimization strategies work best when making a single alteration and repeating the same step-by-step analysis at the early stage of the design process since BIM has the capability to run such iterative analysis.

The sixth green building strategy is the utilization of different sources of renewable energy. The first step to optimizing the use of renewable energy is to reduce the total energy consumption of a building. This goes back to the strategies described earlier involving orientation, massing, and day lighting.

A common example of using BIM for analyzing renewable energy potentials is the photovoltaic (PV). Once a PV type is selected, information such as the intended PV array area (typically roof areas) and the project longitude/latitude to calculate the possible energy production is determined quickly by querying it from the BIM model. Based on a combination of data retrieved from the BIM model and from various online resources, the anticipated energy production can be quickly determined.

The seventh and final strategy identified by Krygiel and Nies (2008) involves the use of sustainable building materials. First, it is necessary for the design team to determine the criteria that cause construction materials to be classified as sustainable and then set what the project needs to achieve these desired criteria. Some of these criteria may involve specifying materials which are non-toxic or that minimize the total amount of embodied energy throughout their life cycle. Presently, BIM tools do not include in their databases information related to material specifications, therefore this will be considered a contributions part of this proposed research.

The development of Green BIM tools, which integrate the design model, can analyze multi-disciplinary information in a single model which improves the analysis and eliminates errors of data handling (Azhar et al., 2011). The intelligent information created by the BIM model can conduct the whole building energy analysis, simulate performance, and visualize appearance (Krygiel & Nies, 2008). This would provide building designers with a direct feedback used to test the design in order to improve buildings performance over their life cycle.

There are still some problems in using BIM for sustainable design. For example, using the BIM tool for energy analysis, currently relies on estimated values for the loads, air flows and heat transfer needed for the simulation, which may result in unreliable estimates (Crosbie et al., 2010). In an example of a LEED Gold certified university building in the U.S., Autodesk Ecotect, underestimated the thermal loads in all field of measurements that were tested and overestimated illuminance levels in about 98% of the field measurements (Vangimalla et al., 2011). Another problem is the data flow between BIM tools and other tools. While the design data can be exported from a BIM model via IFC and gbXML schema, there are some difficulties in this process in the other direction if there is a need to modify the building model to obtain better building performance. Manual configuration is still needed in such cases (Ferrari et al., 2008). Therefore, further development is still required to make the use of BIM for sustainability more efficient and practical.

2.5. Database management system (DBMS)

Coronel and Rob (2009) defined a database management system as a collection of programs which can control and manage a database structure. DBMS provides controlled access to the data stored in the database. The use of a computer database can make for efficient management of the data that can be stored, shared and integrated. The database structure itself is stored as a collection of files. The only way to access this information is by using a database management system (DBMS). The database structure and its applications need to be written by a programmer as an expert using some type of programming language such as Visual Basic or C# (Coronel& Rob, 2009).

The integration of the BIM tool with an external database must meet many requirements and accommodate many workflows, and there is definitely no single method to determine the feasibility or design of such integration. Hence, the only thing that can be supported is specific workflows rather than any one-fits-all approach.

There can be only one side, either the BIM tool or the database (DB), which can contain the primary, main or master source for a particular aspect of data at any time. Tammik (2009) listed different possibilities as follows:

- Some parts can be BIM-owned, e.g. 3D family parametric models or the final instance count.
- Others can be DB-owned, e.g. cost, specific sets or ranges of parameters for families.
- Some might even be allowed to be owned by either application, e.g. a part number or mark.

2.6. Integration and Interoperability

The building life cycle involves organizations with different responsibilities and functions, however there is no specific BIM tool that can support all the functions needed at all stages of the building life cycle. Exchanging the data between applications is essential to the project team in a building. According to Eastman et al. (2008), there are four ways in which model information can be exchanged between two different software tools:

1. Direct links between specific BIM tools;
2. Proprietary Exchange File Format;
3. Public Level Exchange Formats;
5. XML-based exchange formats.

Direct links between specific BIM tools include Open Database Connection (ODBC), Component Object Model (COM) and some proprietary interfaces such as Geographic Description Language (GDL) and Micro Station Development Language (MDL) (Eastman et al, 2008). These programming languages link BIM tools to each other to share the data and information of a building model. The exchanged information from the building model is accessible for exportation, modification, and deletion.

Proprietary exchange file format is a file-based data exchange method. The file format is usually developed by the commercial organization to support its own software product. For example, the Data Exchange Format (DXF), which was introduced by Autodesk, is one of the well-known types of proprietary exchange file formats (Eastman et al. 2008; Eastman et al. 2010; and Arayici et al. 2011). Other proprietary exchange file formats such as SAT, ACIS, STL and 3DS are also developed by commercial organizations to address the functions of their software. These proprietary exchange file formats are developed by the software company for specific purposes, and the limitation of these exchange formats is that they may only be compatible with their own software tools. Public level exchange formats use open standard exchange models which are Industry Foundation Classes (IFC) for building planning, design, and construction management and CIMsteel Integration Standard Version 2 (CIS/2) for structure and fabrication (Eastman et al. 2008; Edwin 2010).

Currently, most BIM tools support IFC models such as Revit Architecture™, Bentley Architecture™, ArchiCAD™, etc. (IFCwiki, 2013). Similar to IFC, CIS/2 also supports many BIM software tools such as SmartPlant4D Structural™, Structural Triforma™, Tekla Structure™ (CIS/2@GT, 2008). The IFC and CIS/2 have been developed based on open formats and international standards. According to NIBS (NIBS, 2007), the IFC data model has become the international standard for data exchange in the building construction industry. These formats enhance interoperability between diverse software tools and integrate the BIM model standard. The limitation is that the BIM model must follow the same standard as the exchange format.

The development, maintenance, and use of IFC and IFC-enabled products is part of the buildingSMART initiative of the International Alliance for Interoperability (IAI). The term “building SMART” means “integrated project working and value-based life cycle management using BIM and IFC” (STAND-INN, 2007). The purpose of IFC within buildingSMART is to enable interoperability between software applications. To satisfy all the requirements the IFC Schema has to be structured in order to allow diversification to cope with the various information axes, as well as centralization to harmonize and integrate the various modules. Wu (2008) describes IFC schema as a single integrated schema used to enable cross discipline, life cycle, and level of detail of data exchange; and as a modular architecture to facilitate the specialization of discipline and life cycle of specific modules within the integrated IFC Schema.

IFC was designed to address all building information such as the inclusion of building performance and sustainability information over the whole building life cycle (Khemlani, 2004). In IFC, each object is defined with its own Global Unique identification. The vision behind buildingSMART is to enable efficient information flow during the complete life cycle of the building. IFC compliant building information models form part of the foundation to this vision (Häkkinen et al., 2008).

As of 2013, the current release of the IFC is version 4. Nisbet (2013) describes it as enhancing the capability of the IFC specification in its main architectural, building service and structural elements with new geometric, parametric and other features.

It also enhances thermal simulations and sustainability assessments and links all IFC property definitions to the buildingSMART data dictionary and improves readability and ease of access to the documentation with numerous implementation concepts and fully linked examples.

Its main improvements that are considered in this proposed research, as stated in buildingSMART (2013), are as follows:

- Standardized quantities for quantity take off, which means definition of international base quantities, defined as separate XML schema + configuration files linked to IFC specification,
- Energy and other performance analysis; improving space boundaries, adding spatial zones and external spaces (against ground, water, air), shading devices,
- Environmental impact values; which includes adding environmental impact indicators and values to the used elements of their types,
- Enhancement of lighting and shading component; including texturing, lighting,
- Connectivity and system models; that are to redesign of the building service part, enhancements on connectivity and documentation update throughout.

The current BIM tools at this time are compatible with IFC 2×3 which consists of four layers as shown in the system architecture of IFC sub-schemas in figure 2.4.

The Resource layer forms the lowest layer in IFC architecture. It provides common resources that are used by classes in the upper layers. For example, all information concerning the basic concept of costs is collected in the cost schema, IfcCostResource in the resource layer. Any class in the core, interoperability, or domain layer that needs to use cost will reference this source (Eastman, 1999). In the core layer, the classes can be referenced by the classes in the upper layers, which are the interoperability and domain layers. The core layer includes two levels of generalization: The Kernel and the Core Extension (Eastman, 1999). The Kernel schema defines the most abstract part of IFC architecture and defines objects and their relationships. Core extensions include generic concepts; for example, the "product extensions" contains the classes of objects that make up the physical description of a building, such as generalizations for walls, space, and roofs.

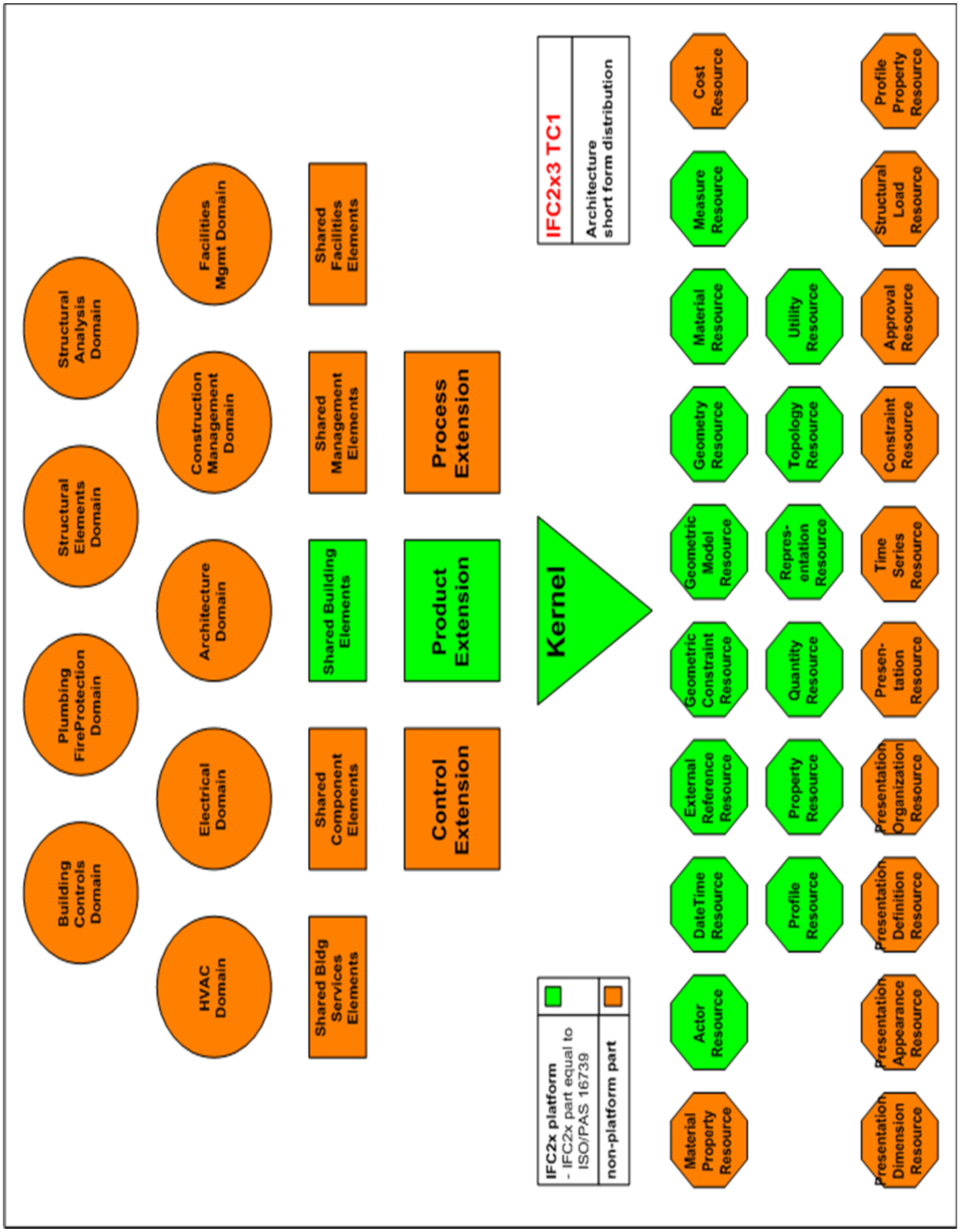

Figure 2. 4. IFC model architecture (Source: IFC Technical Guide: Building Smart, 2009)

The STAND-INN (2007) report series covers a wide range of investigations on IFC support for sustainability. The IFC/BIM and sustainability deliverables of this proposed research were established based on a sustainable construction roadmap using building information models as well as identified IFC/BIM-supported sustainability indicators/applications, especially energy analysis, life-cycle assessment, service life assessment, guidelines for care and maintenance, and guidelines for recycling.

Extensible Markup Language (XML) is popular for information exchange between Web applications to support e-business transactions and customer data collection. An XML schema is a description of a type of XML document, typically expressed in terms of constraints on the structure and content of documents of that type, above and beyond the basic syntactical constraints imposed by XML itself. Current XML schemas in the AEC industry include various formats of XML files such as aecXML, agcXML, gbXML, ifcXML and etc.

Green Building XML (gbXML) helps facilitate the transfer of building properties stored in 3D building information models to engineering analysis tools. Today, gbXML has the industry support of leading 3D BIM vendors such as Autodesk, Bentley, and Graphisoft. Its use streamlines the transfer of building information to and from engineering analysis tools, eliminating the need for time-consuming take-offs.

The gbXML format was developed to facilitate the transferring process for the information stored in building information models to enable integration and interoperability between the design models and other engineering analysis tools (Kumur, 2008). However, gbXML also facilitates the exchange of building information, which includes product characteristics and equipment performance data, between the manufacturer's database, the BIM models and the energy simulation engines. One of gbXML's benefits is its ability to carry detailed descriptions of a single building or a set of buildings, which can be imported and used by energy analysis and simulation tools. The Green Building XML schema was specially developed to facilitate the transfer of information from building information models and to integrate it with design/energy performance analysis (gbXML, 2009). A gbXML document organizes information according to the following hierarchy: Location, Building, Space, Surface, and Opening as shown in figure 2.5.

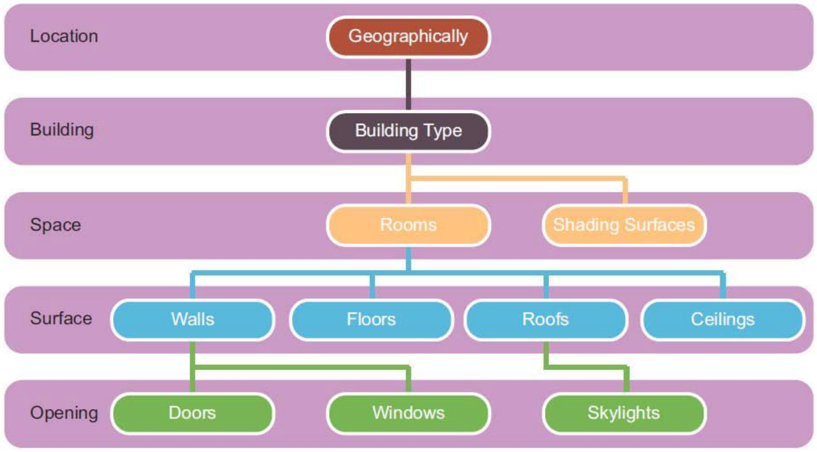

Figure 2.5. Hierarchy diagram of the gbXML schema. (Source: IES/Revit 2010).

The ifcXML representation is an implementation of the ISO-10303 Part 28 Edition 2 standard. This standard provides an XML schema specification that is an automatic conversion from the EXPRESS (ISO 10303 part 1) representation of the IFC schema. The mapping from EXPRESS to XML schema is guided by a configuration file that controls the translation process. For ifcXML this configuration file is standardized and published for each version of the corresponding IFC schema (Nisbet and Liebich, 2007).

The interoperability of BIM tools allows users to pass a more complete and accurate building model from computer applications used by one organization to another with less errors and omissions. Thus all the involved organizations can share consistent building model data at all stages during the building life cycle.

2.7. Functionality of Revit for sustainable design

Revit as a BIM tool includes many functionalities that enable the creation of a comprehensive building information model, which consists of whole building systems including architectural, structural and MEP components. Wu (2010) listed the major functionalities of Revit in terms of BIM and green building design interoperability which is summarized as follows:

1) In Autodesk Revit Architecture, all model information is stored in a single, coordinated database. Revisions and alterations to information are automatically updated throughout the model, which significantly reduces errors;

2) Schedules provide another view of the comprehensive Autodesk Revit model. Changes to a schedule view are automatically reflected in all other views;

3) Interoperability enhancements enable users to work more efficiently. They can also import accurate, data-rich models from Autodesk Inventor software efficiently by speeding up the time to fabrication. With support for different file formats, seamless information exchange between Revit and other critical software application in the project delivery could be realized;

4) Calculate detailed material quantities using the Revit Material Takeoff function. Ideal for use on sustainable design projects and for precise verification of material quantities in cost estimates, Material Takeoff significantly smooth the material quantity tracking process. As projects evolve, the Autodesk Revit Architecture parametric change engine helps ensure material takeoffs are always up to date;

5) Revit supports sustainable design processes from the conceptual stage of the project. It exports building information, including materials and room volumes, to the green building extensible markup language (gbXML) which can be used and studied by variety of energy analysis and building performance software.

2.8. Life Cycle Assessment (LCA)

LCA is a methodology for assessing the environmental performance of a product including a building over its entire life cycle where the environmental performance is measured in terms of a wide range of potential effects e.g. fossil fuel depletion, global warming potential and toxic release to air (Kibert, 2008). It is because of this fact that designers must keep the entire life cycle of the building and its associated materials in mind. This will promote sustainable development practices through suited rating systems by recognizing the projects that implement strategies for better environmental and health performance (USGBC, 2011). A well- performed LCA is a systematically inclusive inventory and impact assessment for each life cycle stage of a given product. The phases for which impacts are determined often include resource extraction, material production, manufacturing, assembly, use, and disposal (reuse, recycling, incineration, or landfill). The American National Standards Institute (ANSI) and the International Organization for Standardization (ISO) have delineated the national and international standard for life cycle assessment with the ISO 14040 environmental management series. Per ISO, LCA is a “compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product or system throughout its life cycle” (ANSI/ISO, 1997). ISO standard states that an LCA incorporates a goal and scope definition, life cycle inventory (LCI), and life cycle impact assessment (LCIA). Interpretation and iteration are also required; thus each step is redefined repeatedly. Figure 2.6 represents ISO’s LCA framework.

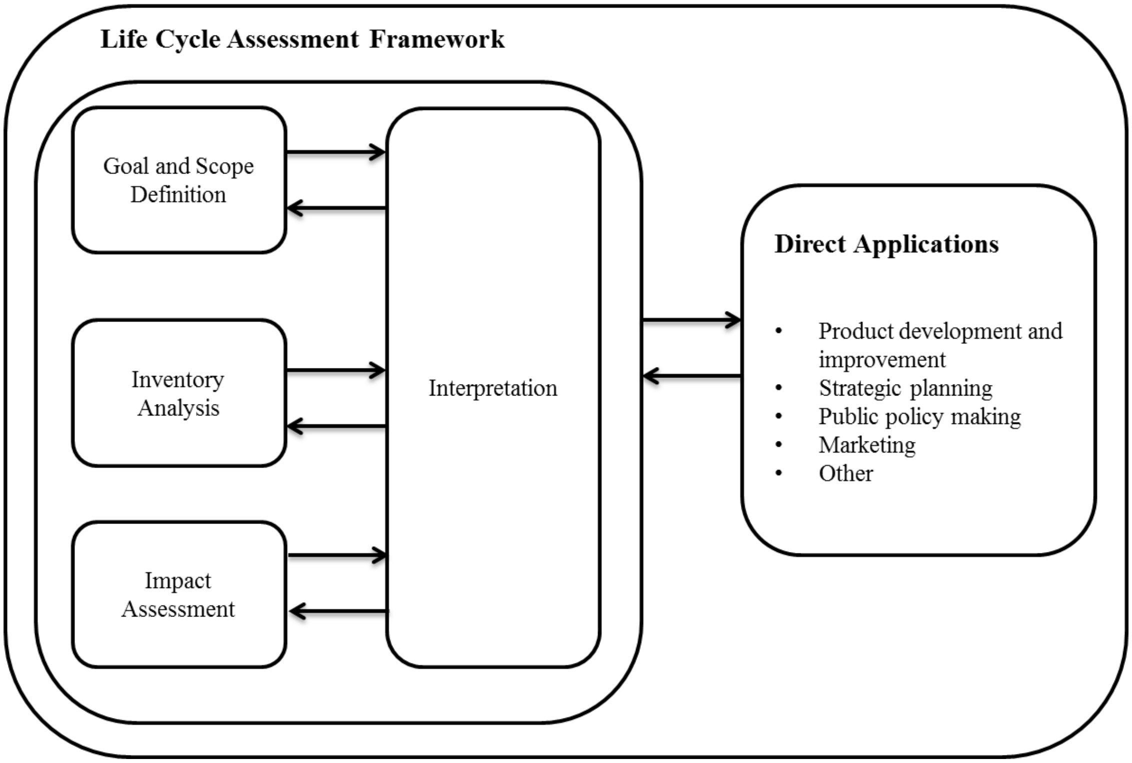

Figure 2.6. Phases of Life Cycle Assessment (ANSI/ ISO, 1997)

LCA is considered as one of the tools used to help achieve sustainable building practices. When the building design process is incorporated with LCA, the designer will be able to assess the life cycle impacts of building systems, materials, and components, and to select the optimum system that decrease the building’s life cycle environmental impact. The focus of designers, when working on a sustainable design, is on their ability to evaluate the EI of the selected products by using available methods and tools. Generally, using BIM tools to design sustainable buildings necessitates the selection of materials and systems so that their EIs can be easily evaluated. Hoff (2008) describes EIs as being the result of the inputs and outputs over a product’s life cycle. Although the total number of different potential EIs may be very large, the U.S. Environmental Protection Agency has categorized the “top ten” impacts as:1) Global Warming Potential; 2)

Ozone Depletion Potential ; 3) Photochemical Oxidant Potential ; 4) Acidification Potential; 5) Eutrophication; 6) Health Toxicity (Cancer); 7) Health Toxicity (Non- Cancer); 8) Health Toxicity (Air Pollutants); 9) Eco-Toxicity Potential; and 10) Fossil Fuel Use. Thus to quantify the impacts of the selected materials on the environment an assessment method has to be applied. The common method used is LCA, which is a tool used for evaluating environmental concerns (Khasreen et al., 2009). The idea of LCA has emerged as the collection and evaluation of the inputs and outputs as well as the potential EI of a product throughout its life cycle (Guinée et al., 2011). Tabone et al. (2010) consider LCA as a tool that quantifies the EI resulting from the production, use, and disposal of a product or process. They classified the benefits of LCA for making informed environmental decisions into the followings: 1) products are compared in defined EI categories, which can be conceptualized by real environmental detriment; 2) unintended environmental trade-offs can be identified between impact categories; and 3) a standardized methodology allows LCA from separate studies to be used to compare product choices. Considerable work has been done to develop systems that assess a building's environmental performance during its life. These systems are developed to evaluate the efficiency of such developments, with a view to balance the economic, environmental, social, and technical aspects (Croome, 2004). There are many tools that measure and assess the whole building based on an LCA tool, such as ATHENA (North America), ENVIST (UK), and Sima Pro (Netherland).

Victorian Native Forest Timbers (VNFT) in 1996 conducted a study on the environmental impact of building materials. A comparison of the energy used over the entire life cycle of residential buildings in four countries concluded that wood-framed buildings consume less energy than steel and concrete buildings. Timber has the lowest carbon released during manufacture, and a net positive effect when carbon stored during the tree's growth phase is included. Glover (2002) also proved that wood and concrete have lower embodied energy values than steel, but quite different ranges (from 0.6 to 41.2 MJ/kg for wood, from 0.9 to 13.1 MJ/kg for concrete). Steel has a significantly higher energy value and range of values (from 8.9 to 59 MJ/kg). The wood components also had the lowest embodied energy values when these isolated component values were applied to the wall, floor, and roof assemblies. A comparison indicates that a wood house contains 232 GJ of embodied energy; a concrete house contains 396 GJ, and a steel house, 553 GJ. An overall uncertainty calculation for each house has given the following ranges for wood from 185 to 280 GJ, for concrete from 265 to 520 GJ, and for steel from 455 to 650 GJ. Overall, mostly-wood houses appear to have the lowest embodied energy levels of the materials (Alshamrani, 2013).

Buckely et al. (2004) used Athena impact estimator to compare the environmental impact of a cast-in-situ concrete system with a structural steel system for the Queen's University Integrated Learning Centre in Kingston, Canada. The case study displayed that the concrete system had less impact on global warming, toxicity, solid emissions, and energy consumption, but required greater resource use than the structural steel system. Overall, the concrete system had less environmental impact than the structural steel system. Lippke et al. (2004) evaluated the environmental performance indicators for typical Atlanta and Minneapolis houses built to code, displaying that with two exceptions, all of the indicators had significantly lower environmental impact for the wood-frame designs in Atlanta and Minneapolis compared to the non-wood frame designs. The steel and wood designs produced similar solid waste in Minneapolis, and the concrete and wood framing designs in Atlanta produced similar water pollution. Concrete framing in Atlanta proved to have lower environmental impacts in comparison to steel and wood-framing in Minneapolis. Haddad (2008) reported that steel framing office building has lower environmental impact than a concrete frame building.

BIM is an organizing concept that contributes in the lifecycle of a facility to create and manage a building’s data in a convenient way. Researchers have looked at the benefits of integrating BIM with LCA and were able to identify the shortages that prevent said integration from taking place. Loh et al. (2007) find that LCA systems are inaccessible and complicated. Fischer et al. (2004) claim that it is inefficient to input data in LCA applications due to the lack of interoperability between different tools and the uncommon data format. Häkkinen and Kiviniemi (2008) identify the following solutions to integrate BIM tools with LCA systems: 1) linking separate software tools via file exchange, 2) adding functionality to existing BIM software, 3) using parametric formats such as Geometric Description Language (GDL). In a recent study, Steel et al. (2010) concluded that BIM tools are useful, not only for design, but also for information exchange between building stakeholders. However, the question of interoperability must be resolved.

LCA tools for buildings still have some limitations and several problems, and the evaluation of the environmental impact of a building is quite complicated due to many changes and circumstances that could occur (Mereb, 2008). Hence, predicting life cycle as "from-cradle-to-grave" for such buildings is very difficult to perform accurately for a long lifetime, such as 50 years (Li, 2006).

In order to analyze the embodied energy of building components, a methodology that integrates BIM models with LCA systems is needed because it would have the potential to streamline LCA processes and facilitate the rigorous management of the environmental footprint of constructed facilities. In LCA terminology, the effects associated with the making, transporting, using and disposing of products are referred to as "embodied effects". Until recently, only operating energy was considered, owing to its larger share in the total energy life cycle. However, due to the advent of energy efficient equipment and appliances, as well as more advanced and effective insulation materials, the potential for curbing operating energy has increased and, as a result, the current emphasis has shifted to include embodied energy in the building materials (Crowther, 1999; Nassen et al. , 2007). Thus, there is a genuine demand for measures to calibrate the performance of buildings in terms of both embodied and operating energy in order to reduce their energy consumption (Langstone et. al, 2008; Treloar et. al., 2001).

2.9. Green building rating system

Green building certification systems can be used to provide design and operations guidance, document progress toward a design or operational performance target, compare buildings using the certification systems structure, and document what design and operations outcomes and/or strategies are being used in the building (Wang et al., 2012).

As the context varies, rating systems in different countries tend to give priority to certain indicators but the general scope is quite consistent. These sustainability indicators embedded in current major green building rating systems address issues in land degradation, biodiversity, water shortage, energy efficiency, renewable energy, carbon emission, air pollution, materials and resources, indoor environmental quality, to name a few.

Several methodologies have been developed to establish the degree of accomplishment of environmental goals, guiding the planning and design processes. Building Research

Establishment Environmental Assessment Method (BREEAM) (Baldwin et al., 1998), Green Star from Australia (GBCA , 2008), the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) from Japan (CASBEE, 2008) , the Building and Environmental Performance Assessment Criteria (BEPAC) from Canada (Cole, 1993), and the Leadership in Energy and Environmental Design (LEED) from the United States (USGBC,2011) were developed and are currently widely applied. Very comprehensive inventories of available tools for environmental assessment methods can be found (Ding, 2008) such as the whole Building Design Guide (WBDG, 2012), and the World Green Building Council (WGBC, 2008).

Although the existing methods and tools have an extended use, LEED has established strong credibility among the experts (Pulselli et. al., 2007). The LEED system was comprised of 7,500 companies and organization members, validating its importance as the standard environmental performance measure of building and becoming a reference system for the design, construction, and operation of green buildings beyond the U.S. (Bowyer, 2007). Furthermore, this proposed research is focused on the North American market, thus the sustainability indicators used by the LEED rating system is of immediate importance to this proposal.

LEED encompass a collection of sustainability indicators to holistically evaluate building performance, or more accurately, how green the building is. The selection of these indicators does not need specialized knowledge since the issues confronting the industry are straightforward and well understood by the professional community, and to a certain extent the general public.

The USGBC introduced the first LEED green building rating system in 1998 as LEED for New Construction (LEED-NC). Then new systems were introduced and LEED became a portfolio as shown in Figure 2.7, and kept evolving over time. The current version is LEED v4, which addresses 21 different market sector adaptations, including new and existing data centers, new and existing warehouse and distribution centers, hospitality, existing schools, existing retail, and multifamily midrise (LEED, 2013). LEED 2009 version including New Construction, Core and Shell, Commercial Interior, Schools and etc.; LEED Online v3 (a web-based tool LEED project teams use to manage the LEED registration and certification processes); and Certification Model (an expanded certification infrastructure based on ISO standards, administered by the Green Building Certification Institute (GBCI) for improved capacity, speed and performance).

One of the goals behind creating the LEED system was to establish a measurement standard for what is considered a green building, comparing them on an even playing field. At the time of creation, some U.S. practitioners were finding it difficult to decipher the claims of their competitors and building product manufacturers who also had started campaigns about how environmentally conscious their products or buildings were (Krygiel et al., 2008).

Figure 2.7. Rating systems categorized in LEED (Source: USGBC 2008).

The LEED standard provides a single score that measures the building's rating or assessment, according to cumulative points in different impact categories, which are then computed to attain a total score. To attain LEED certification, a project must first comply with LEED prerequisite items. Then there are a range of credits that projects can attain to qualify for different LEED certification levels: certified, silver, gold, and platinum, by meeting increasing minimums point levels (Kibert, 2005). LEED Canada-NC 1.0 (NC standard for new construction and major renovations) is the Canadian version of the LEED scoring system. It is approved by the USGBC and was released by the CaGBC in December 2004. An addendum to LEED Canada-NC 1.0 developed 2007 reflects clarifications and improved requirements introduced by the USGBC for LEED-NC 2.2, along with a few other improvements including clarifications regarding the durable building credit. The CaGBC is the source for LEED Canada updates and reference information, including templates.

As an example, in newly constructed buildings for LEED Canada, the points range for each level is varied: from 26 to 32 points (certified), from 33 to 38 points (silver), from 39 to 51 points (gold) and from 52 to 70 points (platinum). LEED certification addresses specific environmental impacts related to buildings utilizing a whole-building environmental performance and assessment approach. The main categories of criteria include: sustainable site (SS), water efficiency (WE), energy and atmosphere (EA), materials and resources (MR), indoor air quality (IQ), and innovation and design process (ID). Each category contains a number of criteria and sub-criteria, some of them are assigned a certain number of credits and others are considered as prerequisites (CaGBC, 2011).

2.10. Energy Analysis and Day lighting Simulation in BIM

For the past 50 years, a variety of building energy simulations and analysis tools have been developed, enhanced and applied by the building industry. Examples of these tools are BLAST, EnergyPlus, eQUEST, TRACE, DOE2, Ecotect and Integrated Environmental Solution (IES-VE) (Crawley et al. 2005). Grobler (2005) claimed that building designs (conceptual and detailed) affect the construction and operation costs of a building. Several researchers describe energy analysis as a holistic evaluation (Abaza, 2008; Dahl et al. 2005; Lam et al. 2004). They claim that decisions made early in a project have a strong effect on the life cycle costs of a building. BIM has received tremendous interest for its impact on the sustainable development and its potential to connect with energy analysis applications. Analysing the energy at the early design stage provides an opportunity to make cost-effective decisions that influence the building life cycle and meet the energy efficiency targets. What BIM brought to energy simulation is an integrative interface that provided the designers a more reliable and consistent building information model for analysis, leading to more accurate simulation results. The biggest advantage of parametric modeling rests in its capacity of updating building information simultaneously with the changes made to the model configuration. In the conceptual design stage, architects and designers could test different design alternatives to find the optimal solution (Wu, 2010). As one of the first official institutions requiring BIM, the U.S. General Service Administration (GSA) leveraged BIM for the submission of major projects for final concept approval. With the use of BIM, the GSA encouraged "accurate energy estimates in the design process" strengthening the adoption of BIM from the early design stages on (GSA, 2008).

Although the potential of using BIM models for energy simulation is well known, a systematic approach that can be used to share the necessary information is still lacking (Young, et al. 2009). The data related to the buildings HVAC systems and to the internal loads such as occupancy and lighting should be included in the data exchanging process between BIM tools and energy simulation software in order to avoid any repetitive data inputs (Pimplikar and Esmaeili, 2012).

The first step to pursue the integration procedure is to test the data inputs and outputs using different interoperable formats and to select the more efficient one. This would provide the design team with the opportunity to compare different energy results for the whole model.

Simulation tools such as Integrated Environmental Solution- Virtual Environment (IES-VE), Ecotect and Green Building Studio (GBS) are able to conduct comprehensive building performance analysis, including energy simulation. GBS and IES have direct interaction with BIM tools such as Autodesk Revit. Ecotect is a building design and environmental analysis tool that covers a broad range of simulation and analysis functions required to understand how a building design will operate and perform. It allows designers to work easily in 3D and apply tools necessary for an energy efficient and sustainable future. Some of its features include a shading design and solar analysis, lighting analysis, acoustic analysis, thermal analysis, ventilation and air flow analysis, building regulations and resource management. Ecotect does not have a plug-in in BIM tools. The way it can get connected with BIM tools is within file format exchanges.

2.10.1. Integrated Environmental Solutions (IES-VE)

(IES-VE) is a great tool that helps users conduct a thorough analysis of the buildings' airflow, thermal dynamic, natural ventilation and daylight assessment. IES has developed Revit plug-in toolbar which allows performance analysis within the same platform. Once the building information model is set up, the user can access the different IES performance analysis products by clicking the relevant button. Each product offers different levels of functionality. IES-VE conducts energy simulation in two major forms: zone-based modeling and room-based modeling. The user may implement one of them or both depending on the stages of the project development and the actual requirements in regard to the simulation results:

Zone-based modeling fits best in conceptual design when floor plan details are not yet developed. It groups spaces with similar thermal conditioning requirements into zones, taking into account solar orientation, occupancy, lighting and equipment loads to estimate the approximate energy consumption as shown in figure 2.8.

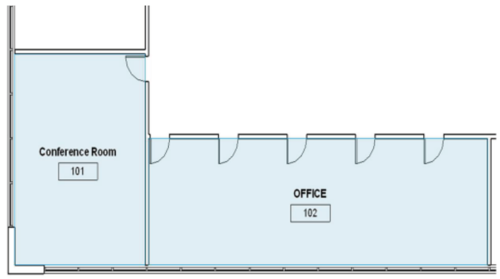

Figure 2.8. Zone-Based Modeling - Floor Plan (IES, 2010)

Room-based modeling is the concept of modeling and defining each room as its own thermal zone. As seen in figure 2.9, It is best during later phase of the project when the design is close to final, since all the information are in the model, it allows for more accurate building performance analysis.

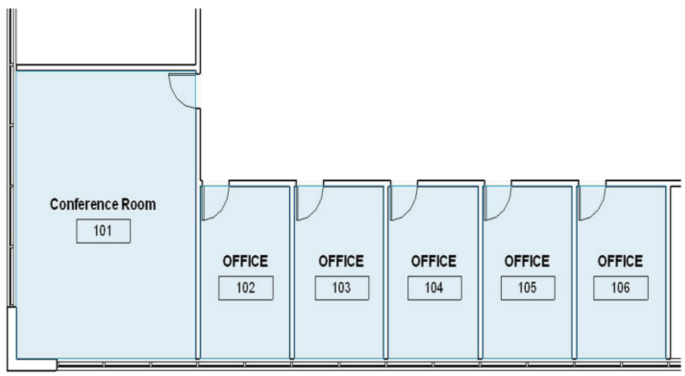

Figure 2.9. Room-Based Modeling - Floor Plan (IES, 2010)

The reporting function of IES-VE is dedicated to presenting a detailed summary of the energy loads per user defined zone or room, categorized into cooling and heating, and air flow, based on the input data extracted from the building information model and the user definition.

2.10.2. Autodesk Ecotect

Ecotect is a tool used to study the thermal and solar gains during the design of proposed buildings. Ecotect was selected because it is easy to use, to create or to clean up models in a format that includes both the geometry and the zones of a building and because it has interoperability potentials with other tools. This interoperability makes Ecotect an ideal tool to import and export 3D models between the BIM tools that generate the geometry of the proposed building and the different advanced energy analysis tools. Ecotect can display and animate complex shadows and reflection of light, can generate interactive sun-path diagrams for an instant overshadowing analysis and can calculate the incident solar radiation on any surface. It can also calculate the monthly heat loads and the hourly temperature graphs for any zone. It can be connected to BIM tool thorough gbXML and IFC file formats.

The IFC file format was developed by the International Alliance for Interoperability (IAI) (IFCs, ISO/PAS 16739, 2005) in the hopes of facilitating the interoperability between different applications and tools. It has an open data exchange format that is usually used by model-based applications to exchange data between one another.

IFC is an international standard that stores building data in a database and permits information (i.e., design, analysis, specification, fabrication, construction and occupancy) to be shared and maintained throughout the life cycle of construction projects (Khemlani, 2004). The IFC model consists of tangible components such as walls, doors, beams and furniture as well as the more abstract concepts of space, geometry, materials, finishes and activities (Kumar, 2008).

Ecotect has a range of import and export capabilities. The Ecotect model can be exported to a host of programs including lighting simulation software like Radiance (*.RAD, *.OCT), ray-tracing program like POV Ray (*.POV), VRML models (*.WRL) and even thermal simulation and analysis software like Energy Plus (*.IDF) and HTB2 (*.TOP). It can export AutoCAD (*.DXF) files and DOE-2 Input files (*.INP) as well a range of others. Ecotect can import files that carry geometric information as well as general data files. Some of the files carrying geometric information that it is able to import include AutoCAD drawing files, (*.DXF), Light scape (*.LP) Light wave (*.LWO) VRML (*.WRL). Some of the general data files that it imports include Green Building XML (*.XML), ASCII model files (*.MOD), Energy plus Input Data files (*.IDF), Weather data files (*.WEA) and Radiance Scene files (*.RAD).

2.10.3. Green Building Studio (GBS)

Among the available tools that have the capability of calculating energy consumption, energy cost and LCC, is Autodesk Green Building Studio© (GBS), which is the most relevant software for this study. It enables collaborative design, allowing sharing building information with other team members, streamlining or eliminating plan take-off tasks, and transferring essential information about design to the applications used for engineering design (Le, 2014). The link between the Revit platform and the GBS web service has been streamlined through a plug-in that enables registered users to access the service directly from their Revit design environment (Autodesk 2008). A key step triggering the conversation between the Revit model and the GBS analysis engine requires the use of gbXML. Based on the building's size, type, and location (which drives electricity and water usage costs), the web-based GBS determines the appropriate material, construction, system and equipment defaults by using regional building standards and codes to make intelligent assumptions. The service uses precise hourly weather data, as well as historical rain data, that are accurate to within 9 miles of a given building site. It also uses emission data for electric power plants across North America and includes the broad range of variables needed to assess carbon neutrality. Usually within minutes (depending on the model size and volume of information), the service calculates the building's carbon emissions where the user can view the output in a web browser, including summaries of the estimated energy and life cycle cost summaries as well as the building's carbon neutral potential. Its direct link with Autodesk Revit through the gbXML format makes it an ideal tool to import and export the 3D design between BIM tools including the geometric data, which is needed to do all necessary analyses. Most building energy cost comparisons and early compliance decisions can be made using annualized energy cost and consumption information. Costs are estimated using statewide average utility rates, or customized rates. GBS allows modifying the base case assumptions and simulating the impact of these modifications on energy efficiency (Le, 2014).

Users can then explore design alternatives by updating the settings used by the service and rerun the analysis, and/or by revising the building model itself in the Revit-based application. Unlike conventional simulation tools that rely heavily on manual data input, IES and GBS obtain building data input with information directly extracted from the established building information model.

2.11. BIM and Cost Estimating

The cost estimating process involves performing Quantity Takeoff (QT), which is a list of quantities of the item and material needed for the project. Traditional QT process with CAD drawings involves selecting individual elements in CAD drawings, using a tool to determine the dimensions for the take-off, and inputting the quantities into the QT list (Khemlani, 2006). This process requires estimators to spend substantial amount of time on generating the QT of the entire drawing. Since the process of selecting and measuring is based on manual operations, the errors and omissions are likely to happen during the QT process.

Since BIM models are object-based with built-in parametric information, it is easier to capture the quantities of the objects in BIM and the QT with BIM drawing will be more accurate with less errors and omissions and the QT process is also expedited because it takes between 50% to 80% of a cost estimator's time on a project (Rundell, 2006). QT process can be enhanced with higher accuracy and less time using BIM technology. Mapping the QT list with cost databases, which can be built-in in BIM models or a standalone external cost database, estimators generate a more accurate and reliable cost estimates of buildings with minimal effort. Based on Jiang (2011), there are three main options to leverage BIM for quantity takeoff and to support cost estimation. They include:

1. Export the building quantities to cost estimating tool,
2. Link the BIM tool directly to the cost estimating tool, and
3. Use a BIM quantity takeoff tool

2.11.1. Export quantities to cost estimating tool

Most BIM tools include functions for extracting the QT from the BIM Model. These tools also include functions to export quantity takeoff data to a spreadsheet or an external database. Microsoft Excel™ is the most commonly used estimating tool which is also sufficient for most estimators where there is no need for users to manually map the cost data with the building components, since the cost data will be mapped as soon as the quantities are generated and assembled.

2.11.2. Linking BIM components to cost estimating tool

Linking BIM model directly to an estimating package through plug-ins tool is another way to link BIM tool with the estimation tools. Some estimating software packages now offer plug-ins to various BIM tools. As an example, Innovaya™ (a BIM cost estimating tool) uses a plug-in tool to link to "Sage Timberline." This plug-in function allows user to associate components in the building model directly with assemblies, recipes, or items in the estimating package in Sage Timberline™ (Jiang, 2011). The user will be able to use rules to calculate the quantities for these items based on their properties or manually enter data that was not extracted automatically from the building information model. The assemblies of building components will follow the rules of Sage Timberline, thus all information required to develop a complete cost estimate can be generated from the BIM Model directly and the building information will be highly integrated and assembled.

2.11.3. Quantity Takeoff tool

Users can choose a takeoff tool specially designed for their needs without having to learn all of the features contained within a given BIM tool. These tools offer varying levels of support for automated extraction and manual takeoff features. The user assembles the objects in the model and dimensional data will be transferred from the model to QT list for further pricing. Visualizing all the items being taken off reduces the chance that the estimator missing items. It also reduces the chance for transposition errors so that if the design changes the linked model updates the estimated quantities (Khemlani, 2006). Example of this is Autodesk quantity takeoff™ which can automatically extract QT from the building model and it also allows manual modification of the takeoffs based on the users' own preference. After that, the QT list can be exported to the MS Excel spreadsheet and users can associate the quantities with any suitable cost database (Jiang, 2011).

2.12. Life-Cycle Cost (LCC)

Life-cycle costing is thus a combination of judgments, predictions and calculations (Ashworth, 1994). Life-Cycle Costing (LCC) is a technique or tool which is used to measure the economics of projects that have different parametric values as to their cash flows over a total life span (ASTM, 2003). It requires that all potential costs be calculated by taking into consideration the time value of money (Dhillon, 2009). The LCC method is used to determine the lowest results or the most cost-effective choice among several alternatives. It can also show that savings could be realized when the higher initial cost of a building reduces long-term future costs such as: maintenance, operation, and repair or replacement costs. In contrast, a lower initial cost will probably lead to an increase in the running costs. The essential objective of life-cycle costing is to evaluate possible alternatives. There are other important factors than the initial capital cost that would have significant contribution to the overall cost throughout the life cycle of the project. Some of these factors are operating, maintenance and repair costs, thermal insulation properties and methods that will affect heating and cooling, appearance and life expectancy. Dell'lsola (2003) in figure 2.10 illustrates the cost types that should be considered in an LCC study by the owners or designers. As can be seen, the Initial Costs contain the total ownership costs related to the initial development of a project. The category of maintenance costs includes the ordinary repair and custodial care, annual maintenance contracts, and the wages of facility personnel performing maintenance tasks (Kirk, 1995). Operation and energy costs include the utility costs such as fuel and electricity consumption costs and the salaries of the personnel needed to run the facility (Dell'lsola, 2003).

Operation and maintenance costs can be provided by the owners or could be obtained from published database, and obtained from the manufacturers (Haviland, 1978). Energy efficiency studies should be performed by designers to forecast utility and fuel costs. Dell'lsola mentions that "Replacement cost is a one-time cost to be incurred in the future in order to maintain the original function of facility or item". The salvage value of the facility is defined as the value that can be recovered at the end of the study period. This value can be obtained from the standard estimating sources: manufacturers, industry associations, owners experience (Haviland, 1978). The meaning of the associated costs may include all of the other identifiable costs not mentioned previously, such as insurance and security costs (Dell'lsola, 2003).

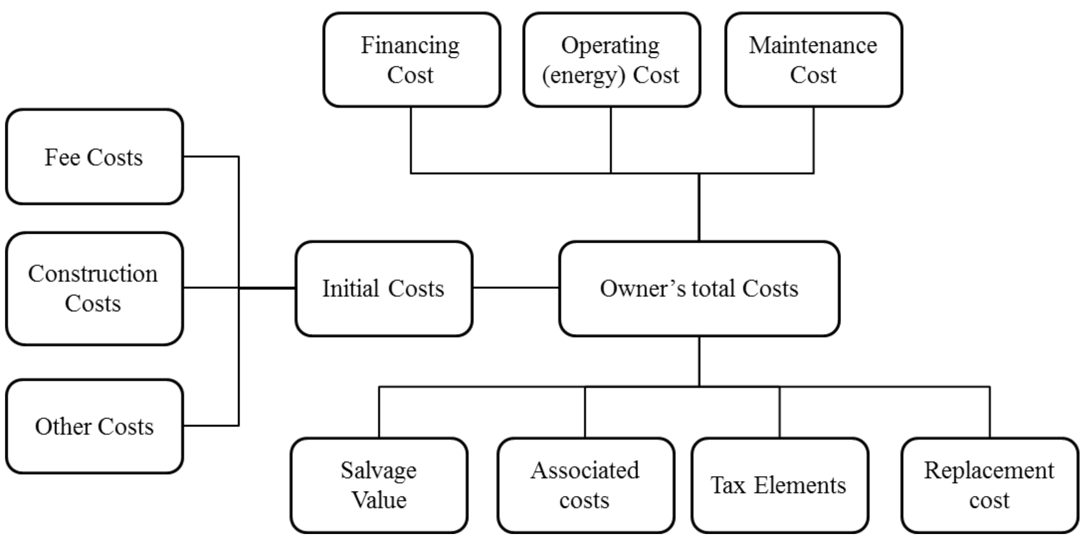

Figure 2.10. Life Cycle Cost Elements (Dell'lsola, 2003)

Life Cycle Cost is the sum cost of owning, running (maintaining & operating), and demolishing over a specific period of time. According to this definition, the LCC equation can be broken down into the following four variables: 1) The relevant costs of ownership: initial cost, running cost, and replacement cost; 2) The future income, such as annual income from rent or the salvage value of building at the end of the study period.; 3) The period of time over which these costs are incurred; and 4) The discount rate (inflation or deflation rate) that should be applied to the future costs to adjust them with current costs (Alshamrani, 2013).

Lowest life-cycle cost (Lowest LCC) method is the most easily-interpreted measure of economic evaluation in construction projects. Some other methods of economic measurements used are Net Savings (or Net Benefits), Savings-to-Investment Ratio (Benefit-to-Cost Ratio), Internal Rate of Return, and Payback Period. These are consistent with the Lowest LCC measure of evaluation method if they use the same parameters and length of the study period (WBDG, 2010).

Operational expenses for energy, water, and other utilities are based on consumption, current rates, and price projections. Since energy and water consumption, and building configuration and envelope are interdependent, operational costs are usually evaluated for the building as a whole rather than for any individual building components. Energy costs are often difficult to be accurately predicted during the conceptual stage of a project's life, therefore assumptions must be made about the historical energy usage, occupancy rates, and weather data that impact the energy consumption. At the conceptual stage, data related to the amount of energy consumed by a building can be retrieved from an engineering energy analysis or from some specific computer applications such as eQuest©, Green Building Studio© (GBS) while other applications like ENERGY PLUS (DOE), DOE-2.1E and BLAST cannot be used at that stage because they require more detailed information and data input that usually is not available until later stage in the design process (WBDG, 2010).

2.13. LCC Implementations in green and non-green buildings

Haddad (2008) introduced a model to measure the environmental impacts of building materials in monetary values. The environmental impact is measured in tonnes in the equivalent carbon dioxide, utilizing a life-cycle assessment tool according to the global warming potential (GWP-100). The quantified equivalent carbon dioxide (CO2) is then converted into a monetary value to be utilized in the LCC calculation of the environmental impact. The economic LCC of building materials is computed based on ASTM's standard technique. The monetary value of CO2 emission is obtained from the stock market, which conforms to the Kyoto protocol's principle of emission trading. “EconoEnviroTLCC Tool” is a web-based design support tool that enables users to calculate the LCC to evaluate and choose the most sustainable building materials.

Alshamrani (2012) conducted a research on evaluation of school buildings using sustainability measures and life cycle costing technique. His research presented the development of a Selection Framework that helps school boards to select cost-effective and sustainable structure and envelope types for new school buildings. The selection procedure is represented based on the LEED rating system and life-cycle cost analysis techniques for typical structure and envelope-type alternatives. In this research, fourteen different structure and envelope types are evaluated with steel, concrete, and wood structures in various combinations covering both conventional and sustainable alternatives.

Even owners and project design team become motivated to consider applying LEED and green building principles; however, cost is still the most important concern. In an ideal world, a methodical assessment of building costs should go further than initial building construction costs which are estimated to be worth only about 5 to 10% of the whole life-cycle costs (Federal Facility Council, 2001). In spite of the significance of LCC, major project decisions in the building industry are more often driven by initial construction costs alone (Matthiessen & Morris, 2004).

Within the context of non-green versus a green building project, the main concern is not the total project cost, but the incremental or additional costs associated with the required green building components, over the cost of the same building without these components. This is commonly called the green cost premium which includes soft and hard costs. The soft costs include LEED registration, certification and documentation, and the related green consulting and design, while the hard construction costs include the green building components (Lisowski, 2006). It becomes a big challenge to find a useful comparison that accurately determines the green cost premium for many building projects, because the green components often take the form of upgraded building systems and materials while the LEED scoring system does not require specific project cost data (Kats, 2003).

Mohan and Loeffert (2011) conducted a study called “Economics of Green Buildings”, which concluded that green buildings could save about 30% in minimizing utility bills over conventional buildings. In addition to direct savings in energy costs, green buildings have the potential of lower insurance premiums, lower waste disposal charges, reduced water and sewer fees, and increased rental rates. Green buildings are designed to be environmentally healthy and energy efficient. However, their initial cost can be 1 to 5% higher than the conventional buildings (Mohan & Loeffert, 2011).

McDonald (2005) investigated the economics of green buildings in Canada via estimating the initial cost premium of five case studies located various provinces across Canada, including building LEED certified building. McDonald proposed seven keys to cost-effective green building: get into a sustainable mindset, establish a clear vision and define the goals, integrate the design process, diffuse knowledge, apply LCC & tunnel through the cost barrier, compensate with brains not stuff, and follow the money trail. The result of this proposal shows that green building is less about product and more about process. Results from five case studies shows that the capital cost of green buildings is 5% less than conventional buildings.

Matthiessen and Morris (2004) conducted a study on the comparison of green versus non-green buildings. Forty-five library, laboratory, and academic classroom projects, designed with some level of LEED certification, were selected for comparison with 93 non-LEED projects of similar types. All costs were adjusted for location and time of construction. Given the common perception that cost of LEED projects is more than non-LEED projects, the analysis was striking. The results displayed no statistically significant difference between LEED and non-LEED projects (Sullivan, 2007). The LEED projects were dispersed through the range of all projects based on cost. It is important to note that the standard deviation of building square footage costs was high, based on the different types of buildings and different square footages of the sample buildings. Overall, the study indicated that typically, 12 LEED points can be earned without changing design, based on the location or siting of a building and local code requirements. Furthermore, up to 18 additional LEED points may be accomplished with minimum design effort at little or no additional cost (Matthiessen, 2004).

Kats (2003) studied the “Costs and Financial Benefits of Green Building”, Cost data was gathered from 33 individual LEED-registered projects (25 office buildings and 8 school buildings) with actual or projected dates of completion between 1995 and 2004. Kats demonstrated conclusively that sustainable building is a cost-effective investment, and his findings should encourage communities across the country to “build green.” This report assumes a 20 year term for benefits in new buildings' inflation. This analysis assumes an inflation rate of 2% per year and a 7% discount rate (i.e., 5% real interest rate plus an assumed 2% inflation). Relatively high California commercial construction costs ranged between \$150/ft^2 to 250/ft^2. A 2% green building premium is the estimated average, which is equivalent to \$3-5/ft^2. The green buildings tested here provided an average 30% reduction in energy use, as compared with the consumption associated with minimum energy code requirements. For energy costs of \$1.47/ft^2/yr, this indicates savings of about \$0.44/ft^2/yr, 117 with a 20-year present value of \$5.48/ft^2. The additional value of peak demand reduction from green buildings is estimated at \$0.025/ft^2/yr, with 20-year present value of \$0.31/ft^2. This report assumed the lower \$5 per ton value of carbon, indicating a 20-year percent value of \$1.18/ft^2 for emissions reductions from green buildings. Green buildings also provide a 20-year percent value of \$0.51/ft^2 for water savings. Calculating rough conservative values for Construction and Demolition diversion in new construction was \$0.03/ft^2 or \$3,000 per 100,000 ft^2 building for construction only. To be conservative, this report assumes that green buildings experience an operation and maintenance cost decline of 5% per year. This equals a savings of \$0.68/ft^2 per year, for a 20-year PV savings of \$8.47/ft^2. Productivity and health values for LEED-certified and silver-rated buildings shows savings of \$36.89/ft^2, while in LEED-gold and platinum these values show a savings of \$55.33/ft^2. The data indicates that the average construction cost premium for green buildings is almost 2%, or about \$4/ft^2 in California, substantially less than is generally perceived. As a conclusion, the NPV for a 20-year time period shows total estimated savings of \$48.87/ft^2 for LEED-certified and silver, and a total estimated saving of \$67.31/ft^2 in LEED-gold and platinum levels. A common way to determine the green cost is to compare the project's final budget with the initial budget. This tends to include all cost coverages, not only those associated with LEED points.

2.14. Design optimization and its effects on LCC

Optimizing design from energy/cost perspective can be seen as a selection problem for the optimum types of building components. These components are mainly roof, floor, doors, windows and walls where the selection is from pre-defined list of available alternatives for each component (Nour, 2012). Ihm et al. (2012) used a sequential search technique to optimize the design of residential buildings in Tunisia. They tried to minimize life cycle energy costs, while increasing building energy efficiency. Xing et al. (2011) adopted the genetic algorithm to optimize building energy design, and their target was to minimize the space conditioning load of an office building located in China. Wang et al. (2005) carried out a multi-objective optimization and improvement of building design. Their study is to assist designers in achieving cost-effective green building design based on the life cycle analysis methodology. Nielsen (2002), Winkler (2002) and Huberman (2007) also conducted research on details about the importance of lifecycle cost analysis and the need for optimization and its modeling challenges. From a cost perspective, designing a building for efficient energy usage is more expensive in the early design and construction phases, but it reduces building costs over the entire lifecycle. Use of Building Information Models (BIM) accompanied with the energy calculations and LCC, ensuring more automatically data flow between different data bases, calculation tools and BIM simplifies the use of LCC in design. Easy access to comparable data gives the design team possibilities to benchmark their buildings, with emphasis on energy use and operation cost. This will lead to more focus on the operation of buildings, as well as improvement of energy optimization (Krigsvoll, 2007). This study aims on incorporating the total annual energy costs of building(s) through a LCC module that uses inputs from the BIM/gbXML module and then providing the results to the project team to make the right decision. Predicting the annual energy consumption however, is a challenging procedure that requires energy simulation by using weather data, thermal properties of used materials for different building components and information related to HVAC systems and other appliances. It is envisaged that the output of the BIM tool would be input to the energy analysis tool by using the gbXML file format (Bazjanac et al., 2011). The major limitation in using energy simulation tools is the issue of their interoperability with BIM. Another limitation is the lack of information needed at the conceptual stage of the project. Since the lifecycle costs of building elements are provided in the form of annual cost per unit area ($/ft2), it is essential to extract the quantities from the model to estimate the cost of every building component. Then, the overall life cycle cost of the building can be calculated. The literature review confirmed the effect of building performance on its Life Cycle Cost and the need of its optimization. This is achieved by using an integrated BIM platform that would be used to select suitable building components from different alternatives that leads to a minimum life cycle costs and energy consumptions.

2.15. Summary

This chapter reviewed the literature about the sustainability and green building concepts and methods of implementing BIM and integrating it into sustainable design as well as reviewing the decision making methods and techniques for sustainable materials' selection. As mentioned before, the characteristics of sustainable design are not only beneficial environmentally, but also economically and financially. Furthermore, green buildings have advantages for owners with regard to reducing the operation cost, saving energy, reducing waste, enhancing indoor air quality (IAQ), and improving occupants' health and productivity. Using a sustainable design approach is very helpful in paving the future of green designs. This chapter also reviews the different decision-making methods and their applications in selecting sustainable materials. This review leads towards developing a methodology to integrate Building Information Modeling concept and Decision Making technique through the development of a module that incorporates a decision support system (DSS), which systematically incorporates the selection of sustainable components and material into a BIM environment. Thus, in this chapter, different areas and definitions, terminologies, previous works and current practices in BIM were described. Its potential link with green building works were also described in details. Integrating BIM and sustainable design and automating the integration process requires the evaluation of different aspects and sub-divisions of sustainable design. Furthermore, the DSS is going to be based on sustainability principles to evaluate green building materials provided by different suppliers and to suggest the best ones that fit the sustainable design requirements.

In this chapter, four main divisions of sustainable design (i.e. LCA, Green Building Rating System and Energy analysis and day lighting simulation and cost) and their tools were reviewed and the possibilities of integration with BIM were taken into consideration through reviewing previous researches.

Numerous types of software used in the construction industry, such as Autodesk Revit Architecture©, Autodesk Ecotect©, Integrated Environmental Solutions (IES-VE) ©, Microsoft Excel©, Athena® Impact Estimator©, Autodesk Green Building Studio© were evaluated.

In this literature review, the integration capabilities of every concept with BIM are analyzed. In LCA and LEED concept, there is no direct link with BIM, but in Energy analysis and lighting simulation, IES-VE has plug-ins in BIM tool and Ecotect can be connected to BIM tool via file exchanges format. The focus is on creating the interface that links both the BIM and the energy modeling tools. By doing so, users will be able to export their BIM conceptual design to gbXML and IFC file formats and import it into the energy modeling tool all from within the BIM model in a fully automated way. Furthermore, the interface should be created to enable users to calculate cumulative LEED points as well as sending BIM quantity take offs to LCA tool for Environmental Impacts (EI). It will allow users to easily evaluate the sustainability of the proposed building conceptual design. One of this proposed research objectives is to collect and store series of design families that will incorporate sustainably certified components in a database, which would improve the workability and capability of the BIM tool to be used when doing sustainable conceptual design. Moreover, the proposed methodology needs to test the capacity of the BIM tool in order to identify the ease of its interoperability with other analysis software.

In this chapter, it was illustrated that BIM provides users with more accurate and consistent project information throughout the lifecycle. Three types of cost estimation methods have been discussed. Furthermore, different methods and models of LCC are identified. By implementing LCC in construction and building projects, it is proved that there is a cost benefit in design and construction of sustainable buildings during the life cycle of the project in comparison with the similar conventional buildings. The literature review also confirmed the effect of buildings' performance on their Life Cycle Cost and the need for optimization. This can be done by using BIM platform that has the ability to select suitable building components between the available alternatives to formulate a building configuration with minimum lifecycle costs including energy consumptions.

CHAPTER 3
RESEARCH METHODOLOGY

3.1. Introduction

This chapter describes the development methodology of a model that integrates BIM with sustainable design at the conceptual stage of building projects, taking into consideration their EIs, energy and lighting analysis, sustainability assessment and cost. The proposed model will simplify the process of designing sustainable buildings, evaluating their environmental impacts, analysing and simulating their energy and lighting, listing their potential accumulated certification points and estimating their life cycle cost. The proposed methodology automates the integration process by customizing and using the APIs of BIM tool to enable users connect their sustainable design with different modules instantly from within BIM tool.

In order to achieve the set objectives of this research, the following procedures are performed as shown in figure 3.1. A comprehensive literature review that covers areas of sustainable design, Building Information Modeling (BIM), integration and interoperability methods in five modules (i.e. DBMS, Energy and lighting analysis, LCA, green building certification system and LCC) as well as the methods that can be used to integrate every module with BIM are studied through the intense literature review.

The data used in the model is collected from the literature, suppliers' web pages, USGBC and CaGBC websites, and published data, then stored in an external database. These data are arranged based on the 16 divisions of the Masterformat work breakdown structure, applied to the library of components stored in the BIM tool and used for implementing sustainable design in 3D mode. The aim of developing a separate database is to have it loaded every time the BIM tool (Revit) opens by defining its path, which is linked to the predefined library of Revit. The data related to the green materials is saved as family files (RFA) or Revit files (RVT), which can be identified by the BIM tool. Thus, in the external database, up to 3,000 design families are collected from the literature, suppliers' web pages, USGBC and CaGBC websites, as well as published data, are stored and arranged based on the 16 divisions of the Masterformat WBS.

Different types of information such as details about the materials used, suppliers' contact data, assigned keynotes, which are textual annotations that relate text strings to specific elements in the model that are in turn linked to an external text file, potential LEED points and assembly codes, are stored in the external database. The external database has updating capability allowing users to enhance it later on by adding new certified components. BIM platform is a suitable environment to establish a Decision Support System (DSS) to help the design team decide on the selection of the best type of sustainable building components and design families for proposed projects based on the Environmental, Economical factors (cost efficiency) and Social wellbeing criteria, in an attempt to identify the influence of design variations on the sustainable performance of the whole building. Afterwards, the design information is transmitted to life cycle cost and energy tools for evaluation and analysis. The proposed methodology incorporates an integrated model capable of guiding users when performing sustainable design for new building projects. Creating and linking such a DSS to BIM tool has the potential to aid designers design and animate sustainable buildings easily and efficiently at the conceptual stage. Part of this integrated methodology is to develop new plug-ins within BIM tool for designers to use when selecting appropriate building components and materials based on project's requirements and attributes in addition to analyse the LCC of different design alternatives.

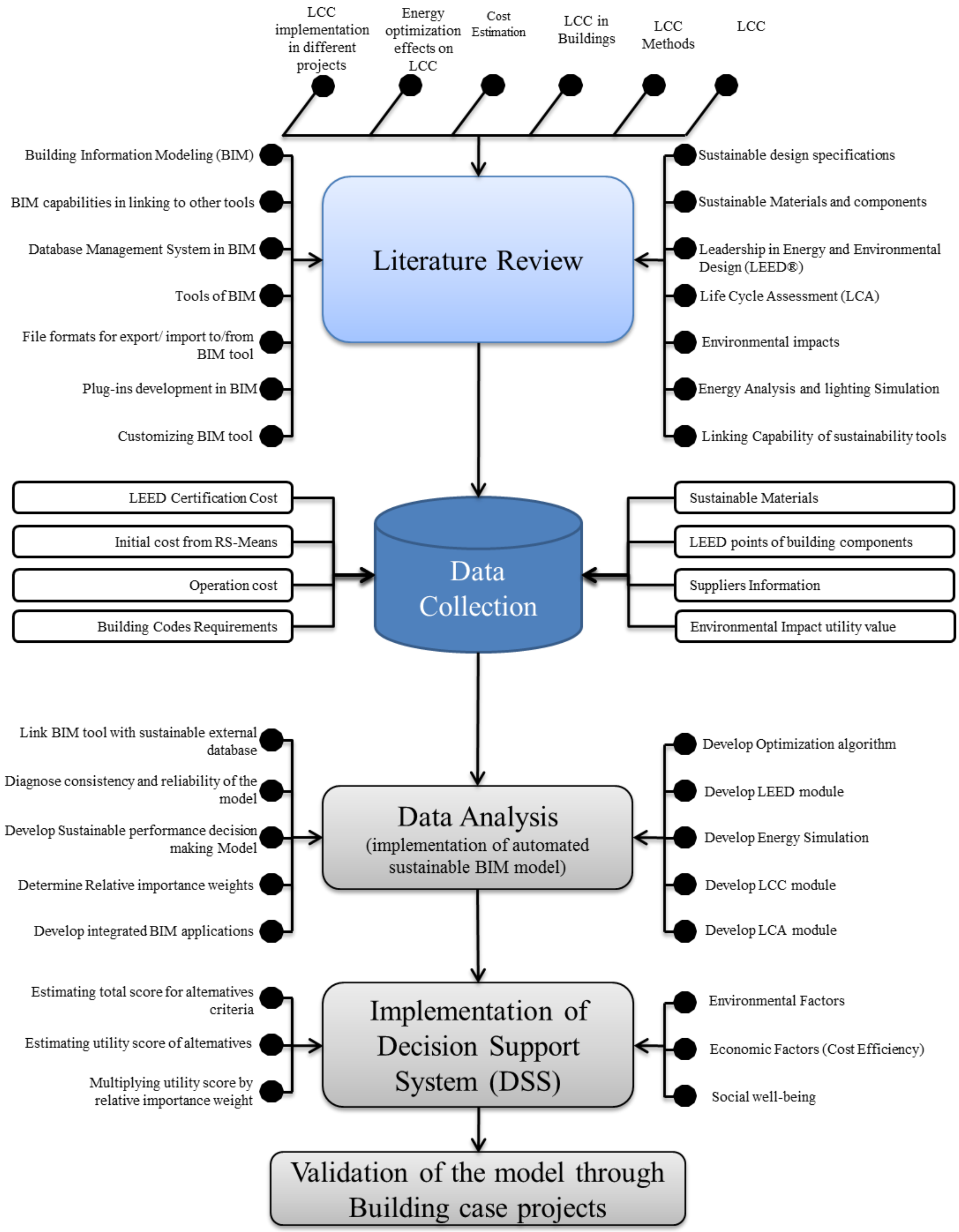

Figure 3.1. Research Methodology

One of this study's objectives is to build and collect a series of design families (architectural and structural) that incorporate sustainably certified components in an effort to improve the workability and capability of the BIM tool used to do sustainable design at the conceptual stage. Moreover, in this proposed research, there is a need to test the ability and interoperability of this tool with other analysis software. Also, an analysis of the information associated with the proposed building model is essential to identify how much of it will be retained and how much will be lost during the process of transforming data from one format to another.

The successful implementation of such a methodology would help owners and designers make reasonable and constructive decisions when selecting sustainable design strategies by using building performance simulations to evaluate the sustainability performance of a building during the early design stage and to evaluate its EI, to analyze its embodied & operational energy, and to simulate its lighting results as well as to list its potentially earned certification points and the associated costs.

3.2. Model Components and Architecture

The integrated model consists of components designed in a modular format, incorporating five modules: DBMS module, BIM module, Energy and Lighting Analysis module, Green Building Rating System module and the Life Cycle Costing module. The BIM module is linked to an external database which is managed by a database management system. The functions performed within each of the model components and their developments are described in succeeding paragraphs.

Figure 3.2 illustrates the proposed model's architecture when the input section includes different parameters related to each module such as project information, sustainable information and Masterformat WBS. The criteria section includes the green building rating system as well as the environmental performance and principles to select green materials. Also, to meet the automation requirements of the integrated model, the programming capabilities of the BIM tool is considered by developing new plug-ins. The main output of the model will be a 3D-BIM sustainable design of a proposed building that includes lists of the selected sustainable materials and their environmental impacts, as well as the results of the energy analysis and daylight data simulation. LCC results of the sustainable building, specifically its running costs and the sensitivity analysis of the three attributes (energy consumption, environmental impacts and cost results), are going to be considered in the outcomes. These results provide valuable information related to a systematic design of a sustainable building where its construction costs are optimized as well as an analysis of the different design parameters and their impact on energy consumption. The novelty highlighted in this proposed research is the integration between its different modules where the data and information are shared among them in an automated way by creating new plug-ins and improving the functionality of the existing ones so that users will be able to start the sustainable design of a proposed building project at the conceptual stage of its life in a timely and cost effective manner. Using a BIM integrated platform moves the design decisions forward from the early stage especially when comparing different design alternatives.

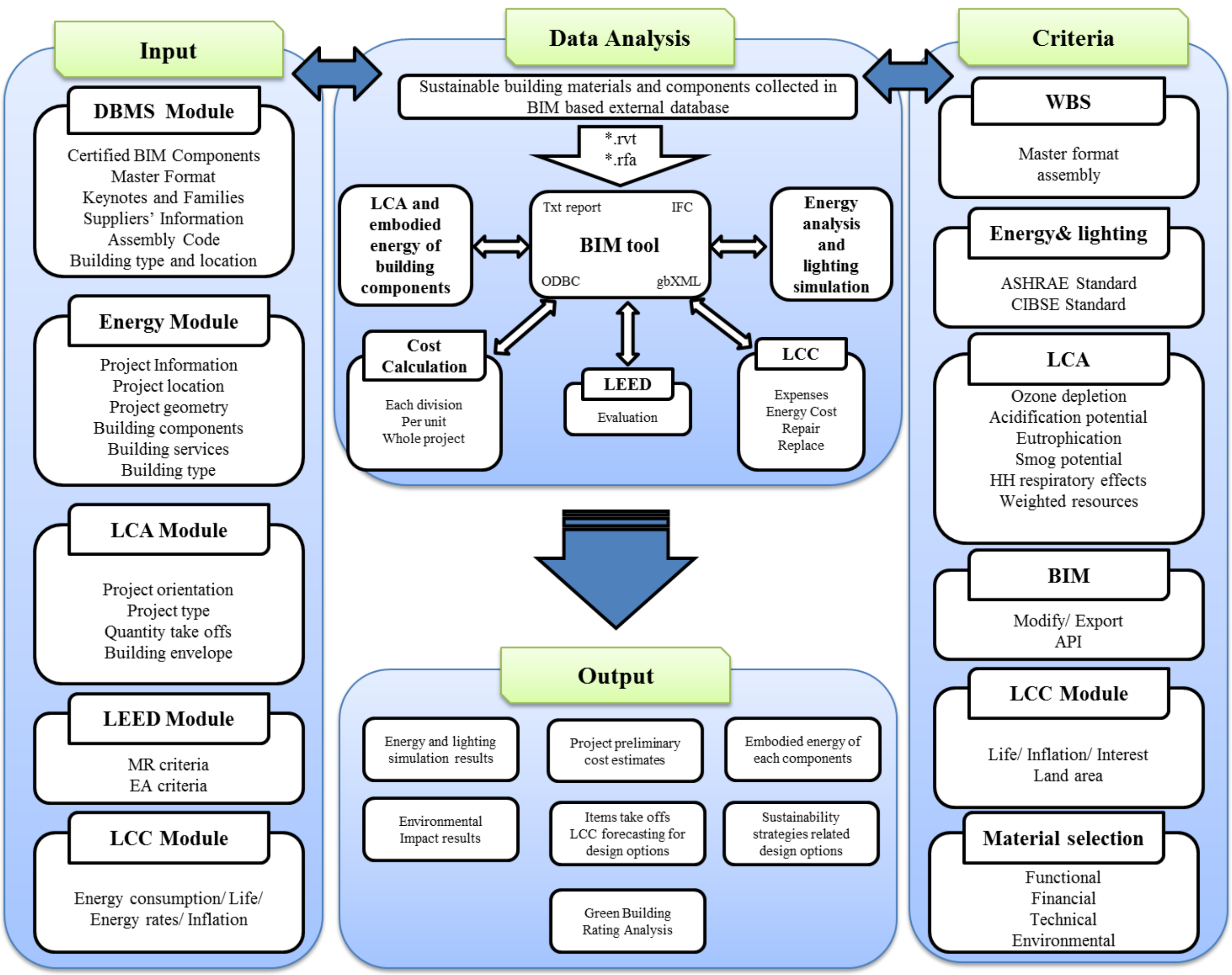

Figure 3.2. Architecture of the proposed model

3.3. Evaluating the sustainable design requirements

The main objective of sustainable design is to create buildings that are livable, comfortable, safe and energy efficient. Sustainable design requires reducing depletion of critical resources (i.e. energy, water, and raw materials) as well as preventing environmental degradation caused by infrastructure and facilities throughout their life cycle (WBDG, 2012). A unique challenge in the AEC industry regarding sustainability is to meet the demands for new and renovated facilities that are accessible, secure and healthy while minimizing their impact on the environment, society and economy. Ideally, building design should result in net positive benefits to all three areas. The Whole Building Design Guide (WBDG, 2012) represents six fundamental principles for sustainable design. 1) Optimize site design including locations of access roads, parking, vehicle barriers, and perimeter lighting; and improve energy performance by reducing the dependence on fossil fuel-derived energy; 2) Use water efficiently and reuse or recycle water for on-site use; 3) Use materials with minimal life-cycle environmental impacts on such things as global warming, resource depletion, and human toxicity; 4) Enhance Indoor Environmental Quality (IEQ) which means maximize day lighting and have appropriate ventilation and moisture control; 5) Optimize acoustic performance; and 6) avoid the use of materials with high Volatile Organic Compound (VOC) emissions. Furthermore, considering the building's operating and maintenance issues during the conceptual design stage will contribute to enhancing the productivity of the building, reducing energy and resource costs, and improving the working environment.

3.4. Evaluating available functionalities of BIM tools

The functionality of the software introduced in previous chapters may not be sufficient to satisfy the sustainable design requirements. For those specifications with available functionalities, an enhancement in the API of the BIM tool will be performed to link requirements and the functionality. For specifications that have complex data requirements, some joint functionality across different tools can resolve the problem. However, in the case that no existing functionality can meet the requirements of certain aspects, a gap will be identified to be evaluated later for a possible solution. As was mentioned in chapter 2 in section 2.5, capability of the DBMS to store materials and specifications, capability of the BIM to see different aspects and modify design as well as calculate detailed material quantities, plus its capability to connect to other tools specially enable the BIM tool to support sustainable design requirements. In addition, since LEED is a point system, the number of points the proposed building can possibly achieve will determine the potential certification level. Thus, it is important for the project team to monitor the accumulated points. The project team will be able to work with the owner to go through the LEED checklist and find a strategy to identify the level of certification they want to target; which credits and how many points to pursue from a cost-benefit perspective; what the essential design and construction challenges faced by the project are, and what the proposed solutions are.

3.5. BIM – Sustainable design integration Model

With the work done in the integration framework part, the integration model will immediately obtain the data requests from the requirements for each sustainable design criterion. All the modules whose requirements can be met with existing functionalities will go through the necessary internal operation in the BIM tool for direct data feedback and eventually be ready for submission to the user. For the modules without support of existing functionalities, two approaches are considered:

- External information from other incompatible applications may still contribute data through the intermediation of IFC and gbXML; and

- New functionalities may have to be developed through customizing the Application Programming Interface (API) and connect it to the BIM tool as a plug-in.

The BIM – sustainable design integration model consists of five major modules as follows:

3.5.1. Module 1: DBMS integrated with BIM

Loucopoulos (1992) states that a consistent information model depends on the integration between databases, programming languages, and software engineering; its lifecycle incorporates the interrelated technologies of conceptual modeling and database design. Based on this statement, designing and implementing the model's relational databases are divided into two steps: the Conceptual Modeling and Implementation Data Model.

This Module consists of designing the model's relational databases which are needed to design sustainable buildings. The design and development of these databases are accomplished in two steps starting with the conceptual modelling and ending with the physical implementation. First, the problem investigation and user needs are recognised based on a comprehensive literature review. Then the database requirements are identified and the conceptual design is carried out. Second, the data model implementation requires that the transformation process be made from the conceptual to the logical design (Jrade and Alkass, 2007). Only afterwards the physical implementation is made by creating a list of related tables used to store the collected data based on the selected Work Breakdown Structure (WBS). The information related to green materials is stored in an external database in the form of predefined design families that can be recognized by BIM tool. The reason for developing a separate database is to have it loaded every time the BIM tool (e.g., Autodesk Revit) opens, which is done by defining its path that is linked to the predefined library of the BIM tool. The data related to green materials is saved as family files with the format of either RFA (family files format) or Revit project file with RVT format, which can be identified by the BIM tool and are added to the existing library of Revit. Thus, in the external sustainable database, over 3,000 design families are collected and assessed from the Smart BIM library webpage (http://library.smartbim.com), suppliers' web pages, the USGBC and CaGBC websites, as well as published data. The SmartBIM Library is a web-based collection of predefined design families, which incorporate detailed information that can be integrated into the design workflow. Due to the big number of companies/factories that produce/supply building products, which are currently available in the market, only leading companies/factories with wider ranges of products have been selected and arranged based on the 16 divisions of the Masterformat WBS. Different types of information such as details about the materials used, suppliers' contact data, assigned keynotes, potential LEED points and assembly codes are stored in the external database. The process of collecting green materials data and storing them in the database is shown in Figure 3.3.

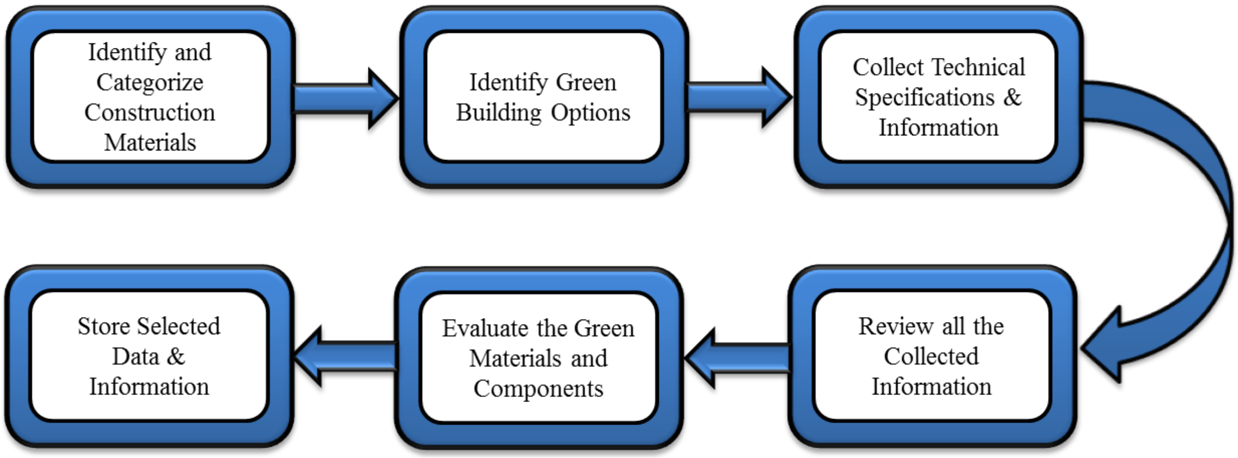

Figure 3.3. Processes of collecting, selecting and storing green materials

An efficient coding system should represent the relationship between the stored data, yet it is important to select a unique code for every single item stored in the database. The coding system allows users to accelerate the process of retrieving necessary information when needed. Thus, a five-digit code representing the division, subdivision, elements and material names is used in storing the collected data. The new design families are based on the modification of the inherited resources in the BIM tool database that occurs when new parameters such as sustainability specifications are added. For instance, the families built into the BIM tool consist of different types of components such as walls, floors, stairs, windows and doors. Therefore, customizing and duplicating the existing families adds an important feature to the proposed model.

3.5.2. Module 2: Energy analysis and lighting simulation

Energy modeling at the conceptual stage is used to provide the design team with first order of magnitude feedback about the impact of various building configurations on annual energy performance. Energy analysis at the conceptual stage requires the designer to make assumptions for a wide range of simulation inputs such as building geometry, building orientation, weather data, heating, ventilation and air conditioning (HVAC) system type and operating characteristics and thermal properties of all construction elements including walls, doors, windows, roof/ceilings and so on. The aim of this analysis is to have an impact on the overall building design, determine the feasibility of concepts in an energy context and to establish energy targets. Figure 4.4 illustrates the procedure used to prepare the building design for energy analysis and lighting simulation. First, the sustainable design should be done using the materials and components stored in the external database as described in module 1. The next step is identifying required information such as project construction type, design geometry, location and defined space objects. The design should provide a proposed building layout including functional and non-functional space configuration and placement of other geometric elements. Non-functional spaces (i.e. technical spaces, shafts, etc.) must be defined by space objects and should not be left as unidentified voids surrounded by geometry. Once the BIM has been prepared for energy analysis, it is exported for energy simulation through gbXML or IFC formats. After selecting the appropriate energy data, weather data and analysis method, the simulation is run. The energy analysis will determine the energy demand (peak load) for the building in addition to the annual energy consumption. Energy demand will be determined for each zone and the total demand obtained for the building by aggregating the zone peak loads for the specified design hour. Energy demand will be determined based on the proposed building space layout, construction type, HVAC system, infiltration, outside air requirements, internal loads by occupants, lighting and equipment and operating schedule. The results will be evaluated directly from the energy simulation output. The results are compared to the energy targets set forth for the project. If the targets are not achieved, then the designer must go back and make further modifications to the building geometry, construction or other building design variables. If the targets are achieved the designer can move forward to the next step. Once the designer is satisfied with the design, a submission package for the owners' review and approval will be prepared. The owners will use a data validation tool to verify that the BIM model meet the requirements of the file exchange and integration. Once the owners' simulation results are verified and approved, an analysis report is prepared comparing the results of the simulation and analysis with those of the designer. Energy performance, operating cost and capital costs (in addition to any other building program requirements) can be evaluated to show the designer whether to go for the design or not. The design feedback package will be delivered back to the designer, and will include either approval or rejection of the design originally submitted by the designer.

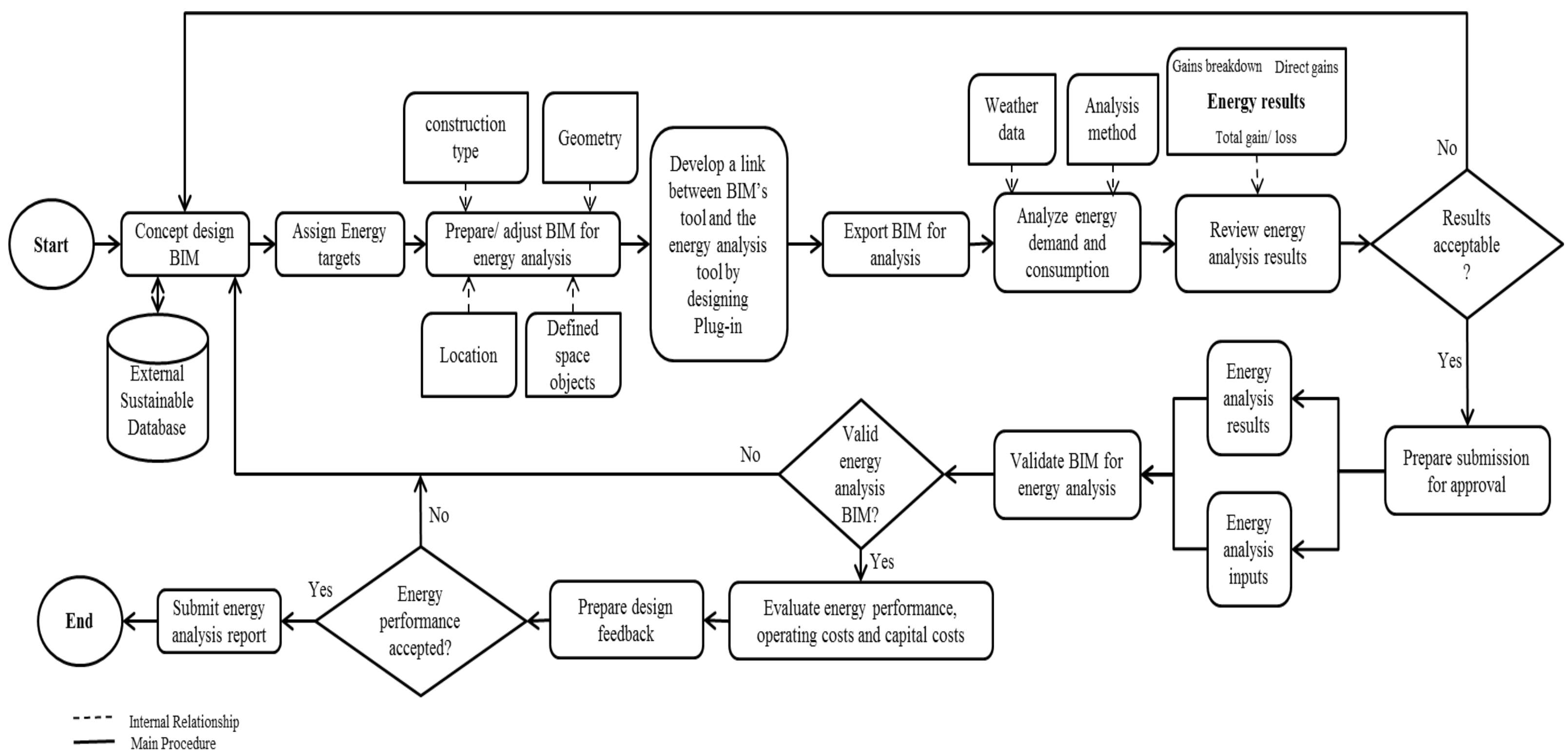

Figure 3. 4. Energy analysis flowchart

The energy module concentrates on developing a plug-in, which is a type of algorithm that adds functionality to the BIM tool by integrating it with the energy analysis and simulation tools. Figure 3.5 represents a sample of the developed algorithm which is used to export the materials quantity take offs to the energy analysis tool using the gbXML and IFC file formats. This algorithm was developed using the C# programming language, producing the plug-ins that will be applied to the BIM tool. In this algorithm exporting the materials quantity take-offs into gbXML and IFC is done automatically and saved in a defined location by the plug-in. Then the plug-in calls the Autodesk Ecotect to pop up and opens the saved files from that location. To load and run the plug-in, an add-in that includes information used by the BIM tool must be added. This is a file located in a specific location checked by the BIM tool when it starts. Therefore, the whole process of transferring data from BIM tool to the energy analysis tool is done automatically using that plug-in.

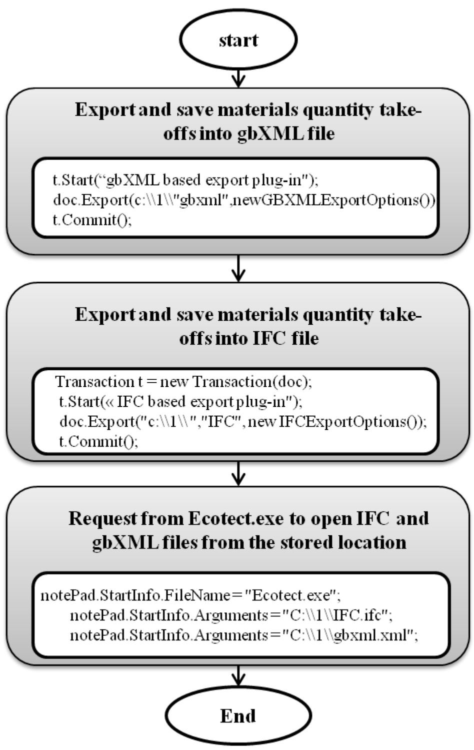

Figure 3.5. Sample of the developed algorithm used to transfer the material quantity take-offs from the BIM tool to energy analysis tool.

One of the energy analysis tools used in this proposal model is Autodesk Ecotect, which is a good tool to study the thermal and solar gains for a proposed building's design. Ecotect is selected because it is easy to use in creating or cleaning up models in a format that includes both the geometry and the zones of a building and because it has interoperability potentials with other tools. This interoperability makes Ecotect an ideal tool used to import and export 3D models that generate the geometry of the proposed building, from the BIM tool to other energy analysis tools. Another tool used in this proposed model is IES-VE, which is used for integrated building performance analysis, thermal analysis, value engineering, cost planning, life cycle analysis, airflow analysis, lighting, and occupant safety (Khemlani, 2006). It also contains an Integrated Data Model, which captures all the information related to the proposed building including the geometric data that is needed to do the necessary analyses. Yet, it must be said that the 3D geometric information can also be exported from the BIM tool using gbXML format. Construction materials can be selected from the IES-VE built-in database, which is called the Apache construction database.

The designer must decide if all the desired design changes have been made and the model is ready for energy simulation. After deciding, the designer uses the model checker to ensure that all the requirements have been met. If the BIM model meets the requirements, the BIM integration is valid. The designer evaluates the results of the energy simulation and compares them to the energy targets for the proposed design. If the design meets the energy targets, as well as any other project performance criteria, the results are acceptable. If not, a modification in design is necessary.

3.5.3. Module 3: Life Cycle Assessment (LCA)

This module concentrates on designing an LCA module that interconnects the 3D BIM design with the LCA tool through an ODBC connection, which directly transfers the materials' quantity take offs to text or spreadsheet format (*.txt or *.xls) in an attempt to evaluate their environmental impacts. The LCA tool is linked to an external database, which is in turn associated with the BIM module that stores the extracted quantities of materials from the 3D design and evaluates their EI as well as embodied energy. The extracted bill of quantity is then linked to the ATHENA® Impact Estimator© in a text exchange file format. The authors elected to use the ATHENA Impact Estimator for Buildings because it is commonly used by the North

American construction industry and because it is designed to evaluate the whole building and its assemblies based on the internationally recognized life cycle assessment (LCA) methodology. This is an important step because LCA analysis outlines how the EIs of all products should be documented and communicated to the owner. Hoff (2008) considers that ISO 14020 calls for the implementation of a standardized format for communicating product EI, called Environmental Product Declaration (EPD). Therefore, LCA should be applied to integrated systems in a building by combining all the EPDs of every selected component in a single EI assessment. The proposed methodology focuses on analyzing the EIs and embodied energy of architectural and structural systems used in the 3D design that are ranked according to their potential certification points. To ease the development process of this module a framework is created as shown in Figure 3.6.

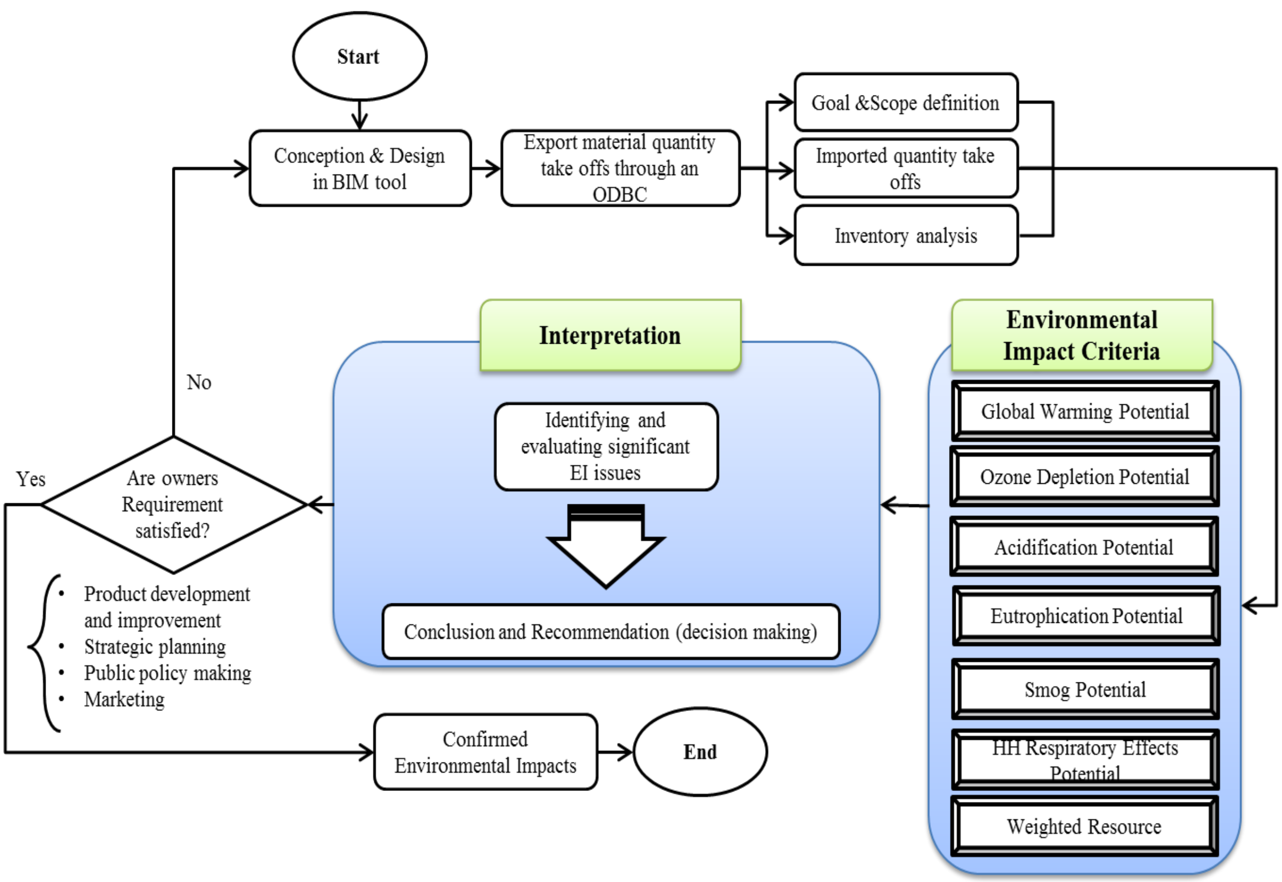

Figure 3.6. Framework of the LCA module

The Impact categories include: 1) air and water pollution, 2) solid waste, 3) Global Warming Potential, 4) primary fuel consumption, 5) weighted resource use, 6) embodied energy and 7) annual operating energy. Documentation provided by the Athena Impact Estimator explains how environmental impact estimates proceed from the input to the final output results. Results from an individual design can be seen in the form of tables or graphs by assembly group and life cycle stages. Detailed tables and graphs show individual energy use by type or form of energy, and emissions by individual substance.

The Athena Impact Estimator (IE) allows users to modify the design, substitute materials and make side-by-side environmental impact comparisons between different building projects. After that, the IE is able to calculate the primary operating energy including the embodied energy (the energy used to extract, refine and deliver energy) and the related emissions to air, water, and land over the life cycle of the building.

3.5.4. Module 4: Green Building Certification and Rating System

As shown in figure 3.7, this module contains data collected from the suppliers' and publishers' webpages, which are retrieved from the created model by developing the sustainability evaluator plug-in that is loaded into the BIM tool. In the results of the sustainability evaluation, there are detailed information about every component, which includes the potential LEED points that can be gained if these materials or components are used in the design. This information is stored in the external database of the BIM tool. The design team can input endless information that is carried with the materials. The plug-in developed for EA and MR credits will rely on these parameters to query availability and cost information. New parameters will need to be created and entered by the model developers. This feature provides ample opportunities for material vendors to advertise their products in the material library. The most important parameters of the elements' information serve the need of knowing which LEED credit is applicable to achieve this credit. These assumptions prove that the optimization tool should be a feature in a new version of Revit (or other BIM software) aimed at designing sustainable buildings. Therefore, when designers model the design for a proposed building project in 3D and select any of these sustainable materials or components, the potential LEED points gained by these selected items are identified and stored in the schedule associated with the BIM model. Afterwards, users will add up these LEED points to identify the potential number that the proposed building can earn and accordingly its potential level of certification (Certified, Silver, Gold, or Platinum). In order to extract the data for LEED certification purposes, the proposed design must be created in a LEED-oriented manner.

This module also calculates the associated cost of registration for the project to be LEED certified and certification related costs. The LEED process consists of three steps: (1) project registration, (2) technical support, and (3) building certification. Only buildings certified by CaGBC under the LEED Green Building Rating System may refer to themselves as LEED buildings. The LEED project certification can be an asset, by receiving third party (CaGBC) confirmation of achieving green principles, and by qualifying for a growing collection of local government and state enterprises. The first step in the LEED process is to register the project with CaGBC and receive orientation documents. Registration during the pre-design phase is highly recommended. Helpful resources are available for users such as LEED Letter Templates, Credit Interpretation Request (CIR) access, and on-line project registration. The second step comes in the form of a Reference Guide and Credit Rulings. In some cases, the design team may encounter questions about the application of a LEED prerequisite or credit to the specific project. The owner should first thoroughly consult the Reference Guide. All this support is available through the credit rulings page on the USGBC web site. The third step is to give the building the attainable certificate; in order to ensure qualification for the specific certificate the application review must be done. This review can take anywhere from six weeks to several months. There are several opportunities for response and request throughout the review stages (administrative, preliminary technical and final technical reviews).

There are four specific criteria for new construction buildings: 1) Prerequisites for the LEED Category. 2) Building Size: part of the certification cost calculation is based on the building area. There are four size categories for the building; these categories are: i) Building Area Less than 2500 m^2; ii) Building Area between 2501 m^2 and 25000 m^2; iii) Building Area between 25001 m^2 and 150,000 m^2; and iv) Building Area more than 150,000 m^2. 3) Number of LEED Components Selected: this will affect the expected type of certification. Each certification type has a minimum and maximum number of points. The total number of points achieved has to be within the ranges as mentioned in the literature review. 4) CaGBC Membership: the status of the projects' owner will affect the calculation of the registration and certification cost where the cost for members will be less as shown in table 3.1.

Table 3.1. Registration and Certification Cost for LEED-NC (CaGBC, 2014)

	Registration		Certification	
	Member	Non-member	Member	Non-member
Standard Review				
2,500 m^2 or less	$600	$900	$4,800	$6,500
2,501-25,000 m^2 (per additional m^2)	$0.14	$0.20	$0.85	$1.15
25,001-150,000m^2 (per additional m^2)	$0.05	$0.06	$0.25	$0.30
>150,000 m^2 (per additional m^2 for certification)	$10,000	$13,000	$0.15	$0.20
Split review: Design review				
2,500 m^2 or less	See standard review	See standard review	$3,890	$5,800
2,501-25,000 m^2 (per additional m^2)	See standard review	See standard review	$0.45	$0.6
25,001-150,000m^2 (per additional m^2)	See standard review	See standard review	$0.13	$0.16
>150,000 m^2 (per additional m^2 for certification)	See standard review	See standard review	$0.08	$0.10
Split review: Construction review				
2,500 m^2 or less	n/a	n/a	$3,890	$5,800
2,501-25,000 m^2 (per additional m^2)	n/a	n/a	$0.45	$0.6
25,001-150,000m^2 (per additional m^2)	n/a	n/a	$0.13	$0.16
>150,000 m^2 (per additional m^2 for certification)	n/a	n/a	$0.08	$0.10

Conceptual methodology is depicted as a data flow diagram. This data flow diagram begins with the data entry level which consists of all the data inputs required for the calculations in the data analysis phase. The input consists of all the data related to the Project (e.g., Project Name, Project Address, Owner Name, Architect, Estimator, Number of Stories, Total Area, Total Cost, Area per Square Foot, and Date). The data entry for this input is done in an input screen. After the user chooses the type of building a new screen will appear started by the LEED certification types. The user then has to select the LEED components for each of the building types (which is either New or Existing) from LEED category EA, IEQ, ID, MR, SS and WE in sequence.

Selecting each of these sub-component categories prompts the user with another screen, which consists of a list of credits that the user has to choose from. The user may choose zero or more credits depending on the project requirements. The user is then guided to select his membership status. For a member of CaGBC the soft cost is less if compared with a non-member who has chosen the same number of credits as that of a member of CaGBC. This soft cost is a part of the output. The output of the model also consists of the other data, which are Accumulated Selected Points and LEED Certificate Type.

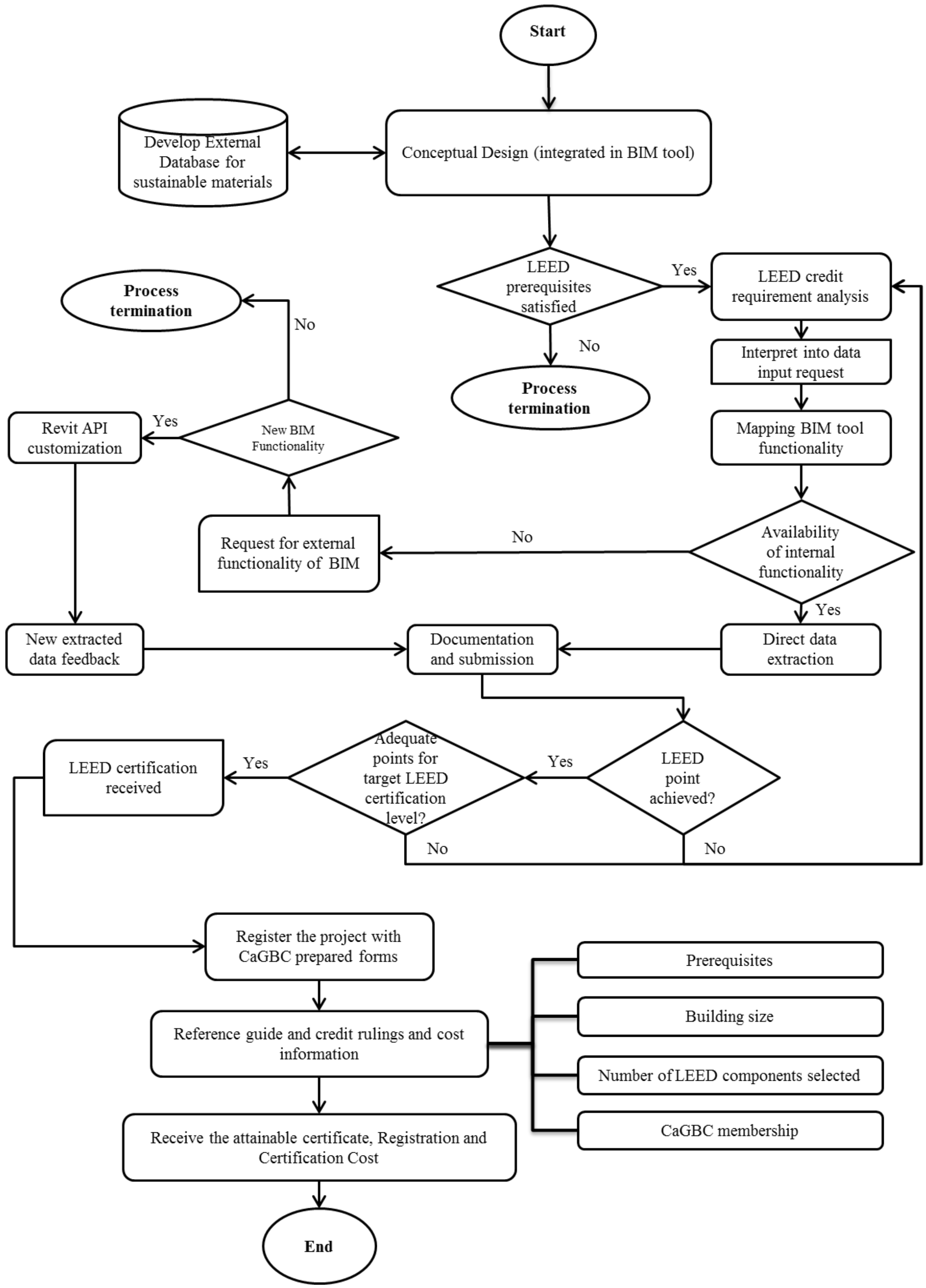

Figure 3.7. The integration between BIM tool and LEED rating system

By implementing the integrated model step by step, the requirements to achieve the MR and EA credits are aimed to be fulfilled. This module is developed and integrated into BIM tool to automate the process of identifying the required number of points that must be accumulated based on the selected LEED certification categories. A plug-in is created into Revit to provide designers the assistance in applying LEED certification management.

3.5.5. Module 5: Life Cycle Cost Analysis (LCC)

This module concentrates on the application of life cycle cost analysis by exporting the 3D design created in BIM tool using the gbXML file format. The LCC procedure starts first by calculating the initial construction costs, which evaluate the capital costs for the existing LEED®-certified buildings. The cost data used in this module is collected from RS- Means publications. Since this study only focuses on the operational cost (energy cost), an evaluation of the total annual energy cost of the created design is computed. Among the available tools that have the capability of calculating the energy consumption, energy cost and implementing LCC analysis is Autodesk Green Building Studio© (GBS). The direct link between GBS and Autodesk Revit through the gbXML format makes GBS as an ideal tool to import and export the 3D design information between the different tools including the geometric data, which is needed to do all the necessary analyses. Most building energy cost comparisons is made by using the annualized energy consumption method and its associated cost and information.

In this study, the outputs extracted from GBS will be used by designers to evaluate the present value and the annual costs as well as to make comparative analysis of the energy savings and emissions reductions. This will help designers evaluate different design alternatives from their initial and operating costs perspectives. The target is to compute and compare the operating cost of these alternatives and to determine the most economical one over the project’s life cycle.

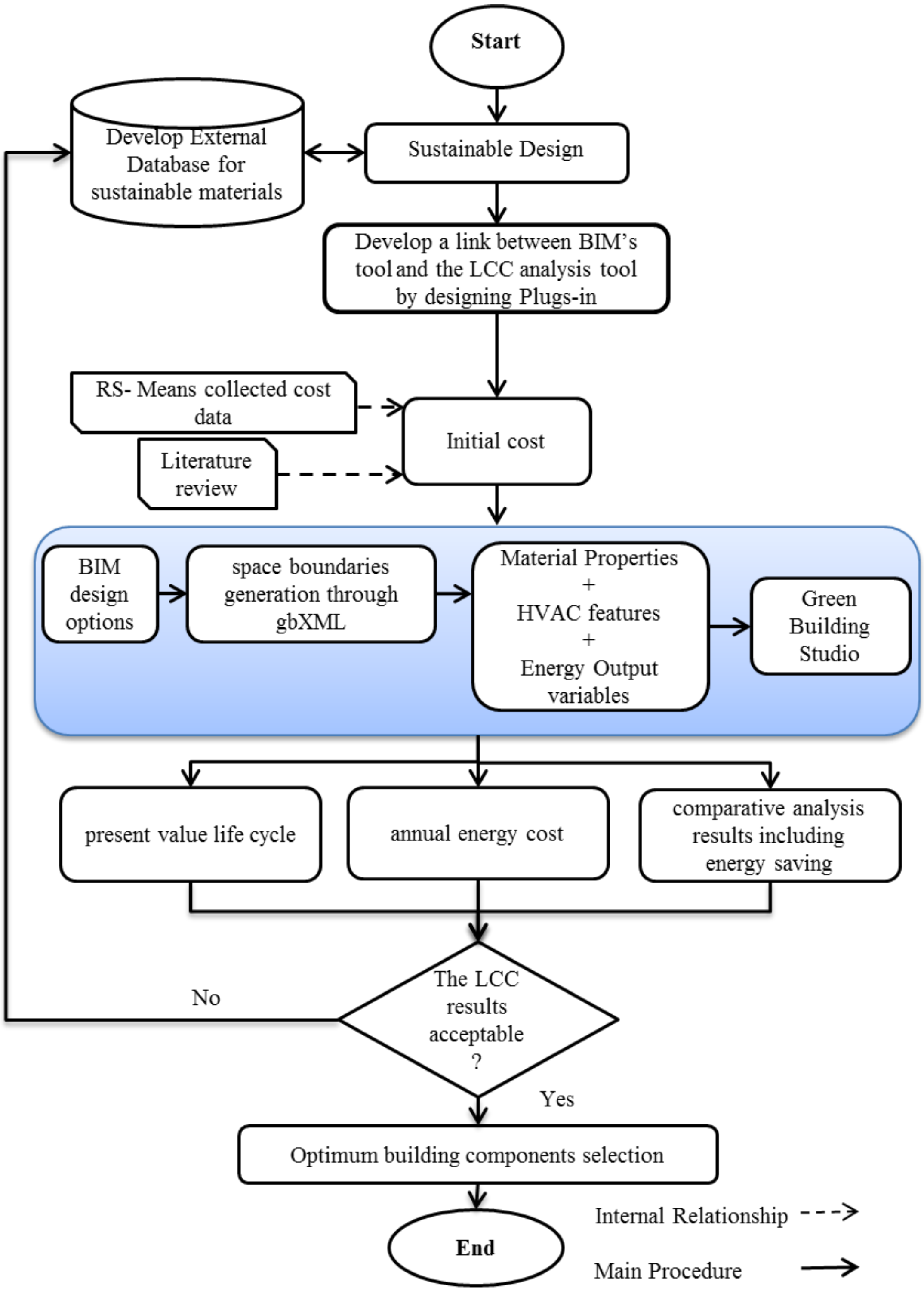

Figure 3.8. The process of life cycle cost analysis to be integrated with BIM

3.6. Decision Support System (DSS) to optimize selection of sustainable building components

One of the main expected contributions of this research is the development of the integrated model that includes a Decision Support System (DSS) used to help the design team in deciding and selecting the best type of sustainable building components and design families for proposed projects based on owners' priorities and requirements. Traditionally, experts used to choose the material whose characteristics are known or by trial and error technique or by employing their previous experiments, which may cause multiple problems related to expectations, standards, and companies budgets. The failure of this traditional method can be handled by using the Multiple Attribute Decision Making approach (MADM), which is basically based on a complex comparison between available alternatives (Shanian et al, 2006).

Figure 3.9 shows a conceptual framework for a DSS module that assists in selecting sustainable construction materials. The DSS uses the conceptual design and decision-making parameters, along with material selection heuristics to generate a list of alternatives for each design component from the materials database. Once the set of alternatives has been generated, the weight factor extractor demands the user to enter weightings for the sustainability attributes. Alternatives in the MADM method are often defined by some attributes that are qualitative (Hwang and Yoon, 1981). For comparison purposes, qualitative attributes need to be converted into quantitative scales. This conversion usually takes place by utilizing five-point Likert-type scales (Lu et al., 2007). Although these scales convert the qualitative attributes to numbers, in many cases, these scales are not able to clearly distinguish the differences between close scores (e.g., high and very high). To solve this problem, Saaty (1980) comes up with a nine-point scale where more intervals have been employed. Values for the sustainability attributes (e.g., the importance factor of every attribute to each other) will be collected from experts in the AEC industry. Then, the user's weightings are integrated with the attribute values for each potential material and sorted to get a relative ranking of the feasible materials for each building component. The building components/products with the highest ranking are recommended by the system. The user reviews the DSS recommendation for each building component, and selects a component for each design element based on his/her professional judgment and/or the system's suggestion. While the building components are selected by the user, the DSS will do an internal check using a built in knowledge-base to detect any potential conflict between the different components and materials. The list of recommended materials for each element is modified automatically as materials are selected for the design components.

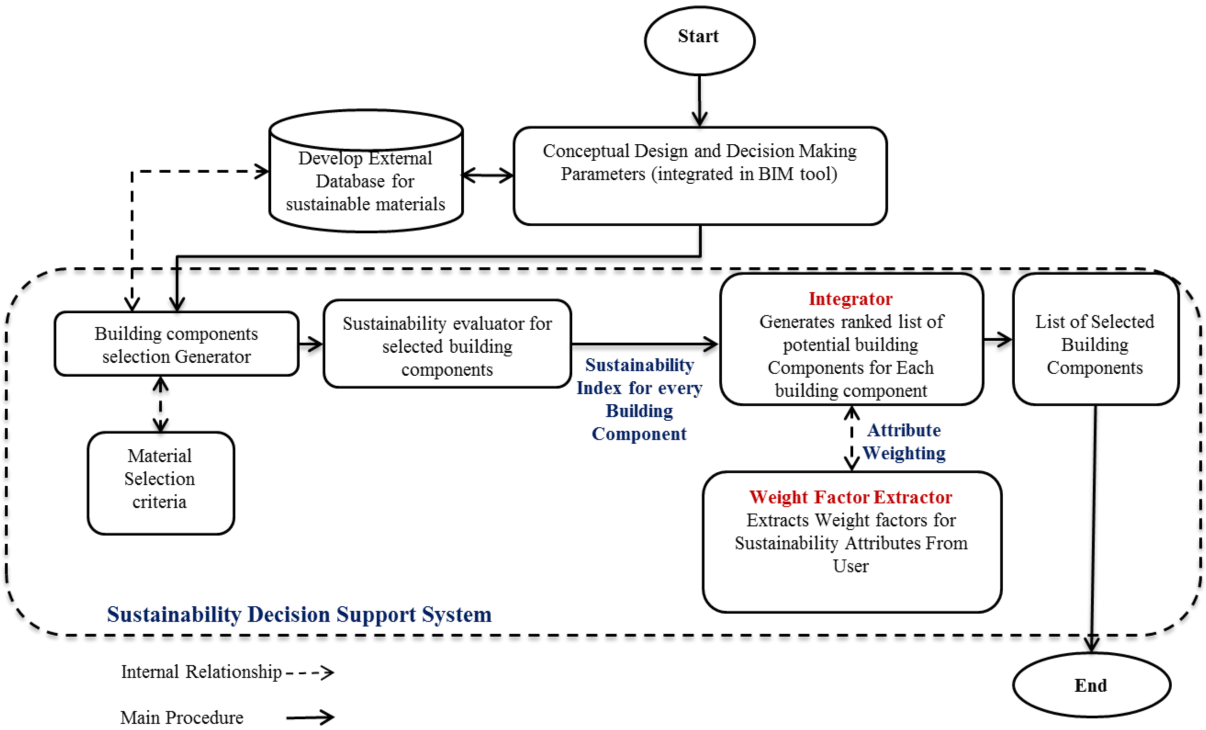

Figure 3.9. DSS conceptual framework integrated with BIM tool

If desired, the user can continue to generate alternative designs by experimenting with other combinations of materials.

3.6.1. Selection and characterization of the TOPSIS method

The unique characteristics of the TOPSIS method make it an ideal choice to solve the material selection problems. In TOPSIS, a vast range of materials' features and all their performance attributes are involved. To implement and use TOPSIS during the material selection process, the main impact of each potential factor that influence that process should be considered with respect to the other factors.

In TOPSIS, the results can be ranked according to their preferences and their numerical values. This ranking gives a clear comprehension of the differences in the preferential alternatives and their similarities, whereas other MADM methods (e.g., ELECTRE) show only the ranking values of the alternatives regardless of their differences and similarities. While working with vast numbers of alternatives and attributes, TOPSIS is more efficient and faster.

The principal objective in TOPSIS is to select the best alternative with the shortest distance from the ideal one (Yoon, 1981). To achieve this goal, we have to find the farthest distance from the negative ideal solution and the closest to the positive ideal solution. The unique features of TOPSIS explains its popularity and efficiency where the vector normalization eliminates the units of criterion function so any change in one attribute can be presented in a direct or opposite behavior by the other factors.

To apply TOPSIS, the following steps are considered:

(a) Step one is to create an evaluation matrix. The basic information of the evaluation matrix can be shown below. This matrix consists of (m) numbers of alternatives ($A_1 \ldots A_m$) and (n) numbers of criteria ($X_1 \ldots X_n$). Each entry (r_{ij}) demonstrates the important relationship between the alternatives and criteria.

	x_1	x_2	....	...	x_n
A_1	r_{11}	r_{12}	...	...	r_{1n}
A_2	r_{21}	r_{22}	...	...	r_{2n}
.	...	...	...	...	...
.	...	...	...	...	...
A_n	r_{m1}	r_{m2}	...	...	r_{mn}

(b) Step two, the following Decision Matrix from step 1 should be normalized. TOPSIS employs the vector normalization, which is done by dividing each attribute value (r_{ij}) by its norm, where the norm is the square root of the summation of the attributes' square values, and n_{ij} represents the dimensionless values of each decision matrix's entries. The normalization is employed by using Equation (3.1).

$$n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}}; \quad j = 1,2, \ldots, n; i = 1,2, \ldots, m \qquad (3.1)$$

(c) Step three is having the associated weight matrix (w_j), which is multiplied by the normalized decision matrix (n_{ij}) to create the weighted decision making matrix (V_{ij}). In this case Equation (3.2) is used.

$V_{ij} = n_{ij}w_j$; j=1, 2,…, n; i=1,2,…,m (3.2)

Where w_j is the single row matrix, which shows the weight of attributes that have been calculated by the Decision Support system according to the factors' relationships towards each other.

(d) Step four, the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) should be determined. The Positive Ideal Solution (PIS) is the maximum value for the benefit attributes and the Negative Ideal Solution is the minimum quantity for cost values.

(e) Step five, calculate the Euclidean distance (S_i^+ ,S_i^-) from the Positive Ideal (V_j^+) and Negative Ideal Solution (V_j^-), Equations (3.3) and (3.4) are utilized for this purpose (Yoon, 1981). For the Positive Ideal (V_j^+), the closet results is exemplary and the farthest distance is optimum for the Negative Ideal Solution (V_j^-).

The term V_{ij} shows the elements in the weighted decision making matrix.

$$S_i^+ = \left\{\sum_{j=1}^{n}\left(V_{ij} - V_j^+\right)^2\right\}^{0.5} \quad j = 1,2,\dots,n; i = 1,2,\dots,m \tag{3.3}$$

$$S_i^- = \left\{\sum_{j=1}^{n}\left(V_{ij} - V_j^-\right)^2\right\}^{0.5} \quad j = 1,2,\dots,n; i = 1,2,\dots,m \tag{3.4}$$

Step six, the closeness index (EI_i) that shows how close the alternatives are to the ideal solutions, can be estimated by using Equation (3.5) (Yoon, 1981) in which S_i^+ ,S_i^- are the positive and negative Euclidean distance from the ideal solutions.

$$EI_i = \frac{S_i^-}{S_i^+ + S_i^-} \; ; i = 1,2,\dots,m; 0 \le EI_i \le 1 \tag{3.5}$$

(f) Step seven, TOPSIS ranks the closeness proportions from the highest to the least, where the highest rank is the ideal alternative.

Shanian et al. (2006) think that in an MADM problem, it is important to know the relative significance of each criterion. As a common approach, the weights are presented in a normalized set in which their total sum equals to one. Meng (1989) consider that Entropy is a measurement of the disorder degree in a system that can also be an indicator that shows the effective information provided by the data. The entropy method can be used not only to quantitatively estimate the data, but also to objectively calculate the relative weight of information (Shannon, 1948). If entropy values are lower, the numerator degrees are more proportional, implying as close to perfect entropy as possible. Conversely, if entropy values are higher, the numerator degrees have a more irregular inflection. Entropy weight method is introduced to obtain the relative weight of each attribute (Qiu, 2002). Each attribute is assigned a measured value to calculate the entropy values. The entropy values for each criterion are then compared, and the relative significance levels of each other are calculated (i.e., the relative weight). Next, the entropy weight is obtained based on the appraisal matrix information.

Pratyush and Jian-Bo (1998) believe that Entropy method is a technique used to evaluate the amount of uncertainty that is represented by a precise probability distribution. Furthermore, Huang (2008) agrees that a broader distribution shows a highest level of uncertainty than does a sharply packed one. Applying the entropy method requires the following two steps:

(1) Step one, Normalization of values

The Entropy method applies a different procedure to normalize the values. Accordingly, it divides the value of each element (r_{ij}) of the weight matrix by the sum of the all elements' values ($\sum_{i=1}^{m} r_{ij}$) to calculate the normalized values of the weight matrix' elements, p_{ij} using Equation (3.6).

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \quad j = 1,2,\dots,m \tag{3.6}$$

(2) Step two, Calculation of the entropy for the criterion

To calculate the entropy values (E_j), Equation (3.7) is employed where k=$\frac{1}{Ln\,(m)}$, (m) is the number of criteria, and (p_{ij}) is the normalized value of the weight matrix elements.

$$E_j = -k \sum_{i=1}^{m} [p_{ij} \ln(p_{ij})] \quad j = 1,2, \dots, J; \quad i = 1,2, \dots, I \qquad (3.7)$$

One benefit of the entropy method is the possibility to mix the decision priorities with the sensitivity analysis. Thus, the final weight is the combination of both them. If the criterion's priorities are similar to the decision-maker's ones then the set of weights can be calculated by using Equation (3.8), where d_j equals$1 - E_j$. In this equation it is considered that all the criteria have the same priority.

$$w_j' = \frac{d_j}{\sum_{j=1}^{n} d_j}, \forall_j, \quad d_j = 1 - E_j, j = 1,2, \dots, J \qquad (3.8)$$

In the case of applying priority based on the project limitations, previous experience or any particular constraint of design, the weights are calculated by using a factor known as λ, which stands for the arranged order of increasing importance of the non-normalized subjective weights. After arranging the assigned weights, the sum of the normalized subjective weights (λ_j) should equal to hundred. The prioritized weights (w_j') can then be calculated using Equation (3.9) in which w_j' is the Entropy weights without considering any priority.

$$w_j' = \frac{\lambda_j w_j'}{\sum_{j=1}^{n} \lambda_j w_j'}, \quad \sum_{i=1}^{n} \lambda_j = 100 \qquad (3.9)$$

3.6.2. Decision Support Systems (DSS) for selecting building materials and components

The sustainability DSS is based on the multi-criteria assessment weighting scale technique combined with Entropy, which enables comparison and ranking of different planning alternatives and scenarios. This is a criterion for the amount of uncertainty through the structured prioritization of a variety of sustainability objectives and indicators. Entropy provides a rational framework for structuring a decision problem by employing a formula which is based on the possibilities (p_i) that are defined before. The other method employed in this DSS, is the TOPSIS Logic which is mixed with a weighted criteria matrix to show the shortest distance from positive ideal solution and the longest distance from the negative ideal solution. The multi-criteria procedure embedded in the DSS relies on numerical models to simulate baseline and alternative situations, as well as ranking the best alternatives based on strategic companies' decision-making teams and available sustainable material in the market; and to provide accurate and detailed results. The set of models included in the DSS describe the relationship between criteria, companies' sustainable materials and interactions that take place in green projects; they have been extensively used in research and practice and have been correspondingly validated within and outside the project. The model inputs come from the sustainable building components which collected and stored in the external BIM database.

The most critical part in this study is the selection and arrangement of the criteria and attributes that affect the selection of sustainable materials for building projects. Basically, the assessment of the attributes is made based on the intense literature review, previous research work and survey completed by experts (information is collected from five sustainable construction material specialists and 25 sustainable design consultants). In this survey, the experts are asked to choose the criteria that have the highest significance on the sustainability of building projects. The criteria for sustainability are divided into three categories: 1) environmental, 2) economical, and 3) social criteria. Each of those categories includes sub-criteria that have been listed in the scoring system completed by experts. Table 3.2 shows the sustainability assessment criteria.

Table 3. 2. Sustainability assessment criteria used for DSS

Main category	Criteria	Sub Criteria
Environmental criteria	Environmental Impacts (EI)	Global Warming Potential Ozone Depletion Potential Acidification Potential Eutrophication Potential Smog Potential HH Respiratory Effects Potential Weighted Resource
	Energy & Atmosphere	Operational energy as Lighting and power, cooling and heating, Minimum Energy Performance, Embodied energy as mining, manufacturing, on site process, transportation and final disposal, Onsite renewable Energy, Energy consumption during building life
	Material & Resources	The application of renewable material, Recycled content
Economical factor (cost efficiency)	Cost	Costs of resources and materials, Labor costs, Operation & Maintenance costs, Renovation and destruction costs

	Investment criteria	The speed of return on investment, Initial investment, Exchange amount
	Time	Approximated Construction time
	Construction issues	Constructability, Flexibility, Material and equipment availability
Social wellbeing	Indoor Environmental Quality (Health of occupants)	Indoor environment comfort, Low-Emitting Materials: Adhesives and Sealants, Low-Emitting Materials: Paints and Coatings, Low-Emitting Materials: Flooring Systems, Low-Emitting Materials: Composite Wood and Agrifiber products, Controllability of System: Lighting & Thermal Comfort
	Design and architecture issues	Daylight and Views, Productivity, Individualization and social identity, Physical space and performance, Aesthetics and architectural issues

3.7. Summary

The steps to develop such an integrated model were as follows:

1. Design and implement an external database to store sustainable materials and building components that will be linked to BIM tool. The database will provide designers with a wide variety of sustainable design options including all the required information related to the environmental criteria.
2. Link BIM tool to this database to automate the preparation of sustainable design based on new parameters set by the owners.
3. Customize BIM tool to automate the process of exporting and importing associated information and parameters of the 3D model to the external database.
4. Connect BIM tool to an energy and lighting analysis tool by creating plug-ins and using the existing functionalities of the energy analysis software to automate the process of analysing energy and lighting simulation during the conceptual design stage.
5. Calculate the environmental impacts and embodied energy of every building component as well as measure the transport energy by linking the BIM quantity take offs to the LCA tool.
6. Calculate the potential LEED points of the proposed design by developing plug-ins in the BIM tool, for Material & Resources (MR) and Energy and Atmosphere (EA) credits.

7. Automate the process of selecting building materials and components, which is integrated in the BIM tool through the use of decision-making problem-solving approaches (i.e. Entropy-TOPSIS) in order to efficiently optimize the selection of sustainable building components at the conceptual design stage of building projects. A Decision Support System (DSS) is developed by using Multiple Criteria Decision Making (MCDM) techniques to aid the design team decide on and select the optimum type of sustainable building components and design families while doing conceptual design of proposed projects.
8. Analyze the operational cost of the whole building within an integrated environment that joins BIM concept and Life Cycle Cost (LCC) method.

This research focuses on the conceptual stage of project life. The purpose is to help decision makers generate a better idea about the project while making important decisions related to the continuation or dismissal of that project. Although the level of accuracy of the available information at that stage is low, decisions have to be taken. Thus, any additional information would be an asset and would be helpful to support the decision. The novelty highlighted in this research represents different modules, which are integrated into each other based on an automated process by creating new plug-ins and improving the functionality of existing ones so that users will be able to start the sustainable design of a proposed building project at the conceptual stage of its life in a timely and cost-effective way. Using a BIM integrated platform moves the design decisions back to an early stage especially when comparing different design alternatives, which is considered a feature of this proposed research. The integration of the proposed methodology can be achieved by implementing an interface written in the visual C# programming language, which is part of MS Visual Studio© especially for the modules that require the creation of new plug-ins.

In the proposed model, multiple design alternatives can be compared based on their economical aspects. The potential results that can be generated by the different modules will be evaluated based on diverse economical perspectives. Energy analysis results will be good feedback to the design team about the potential energy that can be gained or lost within a year by the proposed building. Using this data can ease the way of estimating the energy cost which is a major part of the operation cost for any building. Compared to the traditional method of building estimates, Life Cycle Cost can take a building’s environmental impact and energy aspect into account, which will have a big effect on the future variation of the capital. Along with the obvious environmental advantages, LEED-certified buildings cost less to operate and are more desirable for commercial and residential occupants. In the integration platform, the process of retrieving this information is done in a timely manner and easily with the help of the proposed plug-ins and the database which will store information on a large number of materials and building components.

CHAPTER 4

TECHNICAL PAPER I

INTEGRATING BUILDING INFORMATION MODELLING WITH SUSTAINABILITY TO DESIGN BUILDING PROJECTS AT THE CONCEPTUAL STAGE

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Abstract- Lately the construction industry has become more interested in designing and constructing environmentally friendly buildings (e.g. sustainable buildings) that can provide both high performance and monetary savings. In general, sustainability integrates the following three related components: 1) environmental, 2) economic, 3) social well-being. Incorporating these components at the conceptual stage is achieved by using sustainable design, through which designers must identify associated materials and systems based on any selected certification (rating) system. The use of Building Information Modelling (BIM) concepts helps engineers design digital models that allow owners to visualize the building before the physical implementation takes place. To apply BIM concepts, designers use tools to create 3D models of buildings where the design materials and systems are selected from the built-in database of these tools. Designers will not be able to quantify the environmental impacts of these materials to support the decisions needed to design sustainable buildings due to the following reasons: 1) a lack of information about the sustainable materials that are stored in the database, 2) a lack of interoperability between the design and analysis tools that enable full life cycle assessments (LCAs) of buildings. This paper presents a methodology that integrates BIM and LCA tools with a database for designing sustainable building projects. The methodology describes the development and implementation of a model that incorporates a database in which information about sustainable materials is stored and linked to a BIM (3D) module along with an LCA module and a certification and cost module. The goal of this model is to simplify the process of creating sustainable designs and to evaluate the environmental impacts (EI) of newly designed

buildings at the conceptual stage of their life. An actual building project is presented in order to illustrate the usefulness and capabilities of the developed model.

Keywords: Green Buildings, Sustainability, BIM, LCA, EI, LEED Certification System and Construction Cost Estimating

4.1. Introduction

Achieving a cost-effective building project requires the evaluation and comparison of all the costs and benefits that will occur over its anticipated economic life. In economic terms, a building design is deemed to be cost-effective if it has a lower life cycle cost, which covers its construction and operating costs. The components of a building's life cycle cost include the initial design and construction cost, ongoing operations and maintenance costs, parts replacement, disposal costs or salvage value (WBDG, 2012). In order to meet the requirements of a cost-effective building design, the financial criterion of the selected materials should be taken into consideration.

Studies indicate that lately, the demand for sustainable buildings with minimal environmental impacts is increasing (Biswas et al, 2008). Notably, the construction industry today needs to adopt new technologies for building design to reduce pressures on the environment. An example of these technologies is the green building approach. Incorporating sustainable principles at the conceptual stage is attained by using sustainable design in which designers need to identify associated materials and components based on the selected green building certification system. BIM for instance, is a revolutionary technology that helps engineers design virtual models of a digitally constructed building. This allows owners to visualize the building before it is built. Various design options for sustainability can be studied and tracked in a building information model (Autodesk, 2005). Since BIM allows for multi-disciplinary information to be superimposed through one model, it creates an opportunity for sustainability measures to be incorporated throughout the design process (Autodesk, 2008). Hardin (2009) established three main areas of sustainable design with a direct relationship to BIM. These areas are material selection and use, site selection and management, and systems analysis. Kriegel and Nies (2008) indicated that BIM can aid in the aspects of sustainable design which are building orientation (which can reduce the cost of the project), building massing (to analyze building form and optimize the building envelope), day lighting analysis, water harvesting (reducing water needs in a building), energy modeling (reducing energy needs and analyzing how renewable energy options can contribute to low energy costs), sustainable materials (reducing material needs and using recycled materials) and site and logistics management (to reduce waste and carbon footprints). Generally, using the BIM tools to design sustainable buildings necessitates the selection of materials and systems so that their environmental impacts (EIs) can be easily evaluated.

Hoff (2008) describes EIs as being the result of the inputs and outputs over a product's life cycle. Although the total number of different potential EIs may be very large, the U.S. Environmental Protection Agency has categorized the "top ten" impacts as: 1) Global Warming Potential, 2) Ozone Depletion Potential, 3) Photochemical Oxidant Potential, 4) Acidification Potential, 5) Eutrophication, 6) Health Toxicity (Cancer), 7) Health Toxicity (Non- Cancer), 8) Health Toxicity (Air Pollutants), 9) Eco-Toxicity Potential, 10) Fossil Fuel Use. Thus, to quantify the impacts of the selected materials on the environment, an assessment method has to be applied. The common method employed is LCA, which is a tool used for evaluating environmental concerns (Khasreen et al., 2009). It is because of this that designers must keep the entire life cycle of the building and its associated materials in mind. This will promote sustainable development practices through suited rating systems by recognizing the projects that implement strategies for better environmental and health performance (USGBC, 2011). This paper focuses on integrating BIM with LCA for designing sustainable buildings at the conceptual stage with the emphasis on their associated materials.

4.2. Literature Review

The early design and preconstruction phases of a building are the most critical times to make decisions on its sustainability features (Azhar S. et al., 2009). The focus of designers when working on a sustainable design is on their ability to evaluate the EI of the selected products by using available methods and tools. The idea of LCA has emerged as the collection and evaluation of the inputs and outputs as well as the potential EI of a product throughout its life cycle (Guinée et al., 2011). While LCA can be used to assess the sustainability of the built environment, its technique provides comprehensive coverage of the product's EI, therefore it is very useful to apply it at the conceptual design phase of building projects. At that stage the designer must be able to acquire, store, and organize LCA data for the components in such a way that it can be used to generate feedback during the design process (Ries and Mahdavi, 2001). Traditional computer-aided design (CAD) usually lacks the ability to perform sustainability analyses at the early stages of design development. Meanwhile, BIM represents both the graphical and non-graphical aspects of a building (Eastman et al., 2008), and it offers a database which represents ‘‘the truth’’ in a reliable manner at any given moment in time, which encourages collaboration (McGraw-Hill Construction, 2009; Thomson & Miner, 2006). It takes a multi-dimensional approach, allowing the building team to see how the pieces of their project fit together in real time (McFarlane, 2008). Objects in BIM models not only serve as physical placeholder, but also represent a set of information attached to all the necessary data such as supplier information and maintenance procedures (Thomson & Miner, 2006). With the use of BIM, a building can first be constructed virtually on a computer before it is actually built in the field (GSA, 2007). It helps owners visualize the spatial organization of the building as well as understand the sequence of construction activities and project duration (Eastman et al., 2008).

The combination of sustainable design strategies and BIM technology has the potential to change traditional design practices and to efficiently produce a high-performance design. BIM technology can be used to support the design and analysis of building system in the early design process. It includes experimental analysis of structure, environmental controls, construction method, use of new materials, or systems and detailed analysis of user processes. In the field of building system analysis, it involves many functional aspects of the building system, such as structural integrity, ventilation, temperature control, circulation, lighting, energy distribution, and consumption (Azhar S. et al., 2010).

BIM is an organizing concept that contributes in the lifecycle of a facility to create and manage a building’s data in a convenient way. BIM technology today has limited impact on the green building process, but it can be enhanced by changing the future design of green building by including valuable tools. New information technology tools that help narrow the existing gaps related to building design and its impact on the environment is needed.

A methodology that integrates BIM models and LCA systems is needed because it would have the potential to streamline LCA processes and facilitate rigorous management of the environmental footprint of constructed facilities. Researchers have looked at the benefits of integrating BIM with LCA and were able to identify the shortages that prevent said integration from taking place. Loh et al. (2007) find that LCA systems are inaccessible and complicated. Fischer et al. (2004) claim that it is inefficient to input data in LCA applications due to the lack of interoperability between different tools and the uncommon type of data format. Häkkinen and Kiviniemi (2008) identify the following solutions to integrate BIM tools with LCA systems: 1) linking separate software tools via file exchange, 2) adding functionality to existing BIM software, 3) using parametric formats such as Geometric Description Language (GDL). In a recent study, Steel et al. (2010) concluded that BIM tools are useful, not only for design, but also for information exchange between building stakeholders. However, to allow these propositions become a reality, the question of interoperability must be resolved. This paper adopts the method of communication between BIM and LCA tools to be through a text file exchange way.

Green building certification systems can be used as guidance for design, to document performance progress, to compare buildings, and to document the outcomes and/or strategies used in the building (N. Wang et al., 2012). Several methodologies such as: Building Research Establishment Environmental Assessment Method (BREEAM) (Baldwin R et al., 1998), Green Star from Australia (GBCA , 2008), the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) from Japan (CASBEE, 2008), the Building and Environmental Performance Assessment Criteria (BEPAC) from Canada (R.J. Cole , 1993), and the Leadership in Energy and Environmental Design (LEED) from the United States (USGBC, 2001) were developed and are widely applied to establish the level of accomplishment of the environmental goals and to guide the planning and design processes. Apart from that, Ding (2008) claims that comprehensive tools for environmental assessment can be found (i.e., whole Building Design Guide (WBDG, 2012), the World Green Building Council (WGBC, 2008))

Although the existing tools have an extended use, LEED Rating System (LEED-RS) has established strong credibility among experts (Pulselli et Al., 2007). The validation of the LEED-RS to evaluate its importance as a measurement tool for the environmental performance of a building was implemented by 7,500 companies and organization members.

In this paper, the process of integrating BIM and sustainable design is pursued by developing an external database that is linked to BIM tools. This database includes information about certified components that are recognized by BIM tools. This information includes links for the manufacturers' webpage, contact information, costs, as well as potential LEED points for every selected building component. Linking the customized BIM tools with LCA applications is discussed in further details in the succeeding paragraphs.

4.3. Scope and significance of the study

This paper describes a methodology that can be used to implement sustainable design for proposed buildings at their conceptual stage, taking into consideration their EIs. The methodology is implemented through the design and development of a model that simplifies the process of designing sustainable buildings, evaluating their environmental impacts, and listing their potential accumulated certification points. The methodology emphasizes the integration of BIM, Management Information System, and LCA, thereby providing a reliable tool to owners, architects, engineers, and all participants involved in the design and construction of sustainable buildings. The methodology incorporates an integrated model capable of guiding users when performing sustainable design for building projects. It incorporates three modules: 1) 3D (BIM) module, 2) LCA module, 3) green building certification and cost module. Each of these modules is linked to one or more databases containing necessary data and information. Numerous types of software used in the construction industry such as Autodesk Revit Architecture©, Microsoft Excel©, and Athena® Impact Estimator© were used in the development of this integrated model.

The successful implementation of such a methodology represents a significant advancement in the ability to attain the sustainable design of a building during the early stages, to evaluate its EI, and to list its earned certification points and associated costs.

4.4. Methodology

The aim is to develop an automated way through which sustainable design in 3D mode will be accomplished and all related earned certification points and their costs identified. In order to attain this objective, the following steps need to be carried out:

4.4.1. Data Collection

The data used in the model is collected from the literature, suppliers' web pages, USGBC and CaGBC websites, and published data. These data are arranged based on the 16 Masterformat divisions, applied to the library of components stored in BIM's tool and used for implementing sustainable design in 3D mode. The aim of developing a separate database is to have it loaded every time the BIM's tool opens. This is done by defining its path, which is linked to the predefined library of the BMI's tool. Furthermore, the developed database contains information regarding around 3,000 green components, which are arranged based on the 16 divisions of the Masterformat work breakdown structure. Therefore, users are capable of researching and selecting a variety of sustainable components from the database with their associated specifications, potential LEED points, and manufacturer contact information. Also, users can enhance the database later on by adding new certified components.

4.4.2. Development of the Model

Since the model integrates different applications, the development is carried out through the following four phases:

- Phase 1 consists of creating the relational database the model needs to design sustainable buildings.
- Phase 2 includes the design of the 3D (BIM) module and to customize BIM's tool (Autodesk Revit©) by creating new families and keynotes that have 3D elements for the building's components.
- Phase 3 consists of designing an LCA module that interconnects the 3D design with the LCA tool to evaluate its impacts on the environment.
- Phase 4 incorporates the design of a green certification module that provides a list of the potential earned points and associated costs for the 3D design of phase 2.

Each of these phases is discussed separately in the following paragraphs.

4.4.3. Model Components and Architecture

The model consists of components designed in a modular format, incorporating the foregoing modules. Figure 4.1 shows the model's components. 3D (BIM) module includes components and families, keynotes, as well as 2D and 3D models linked and stored in an external database based on the Masterformat work breakdown structure (WBS). For instance, the information about different parts of each green family such as Windows is saved in the external database. Based on the selected materials and systems used in the 3D model, the LCA module will be able to evaluate their EIs and generate required reports. Then, the Green certification system module quantifies the potential number of earned points. The potential points that can be earned by each green family are already provided by their suppliers and stored in the external database. The associated cost of the design in the 3D model is calculated based on published data. Figure 4.2 shows the model's architecture; it determines the processes for data analysis considering all criteria and specifications. This analysis is applied on the selected materials' Environmental Impacts, divisions, Energy Efficiency, green building rating system, and sustainability issues using input requirements. These, in turn, include the project information, sustainable information, Masterformat work breakdown structure with the consideration of criteria such as green building rating system, Environmental Performance, project type, and unit cost of green materials. The main output of the model is a 3D-BIM sustainable design of the building containing lists of the selected sustainable materials and their environmental impacts, the cumulative points, and associated costs. The innovation highlighted in this paper describes the model's modules, which are integrated together so that the user will be able to start the sustainable design of a project at the conceptual stage of its life.

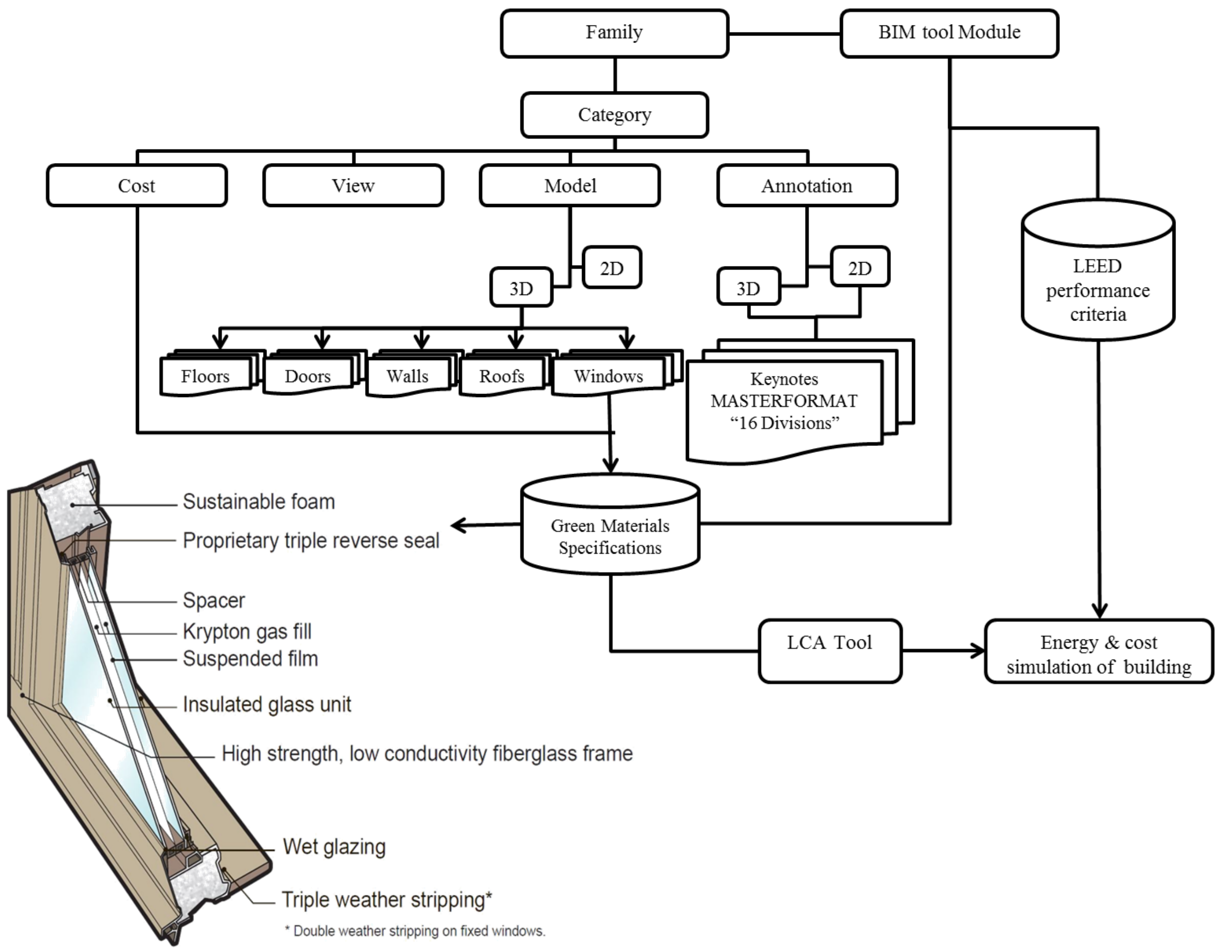

Figure 4. 1. Figure1 Developed model's components

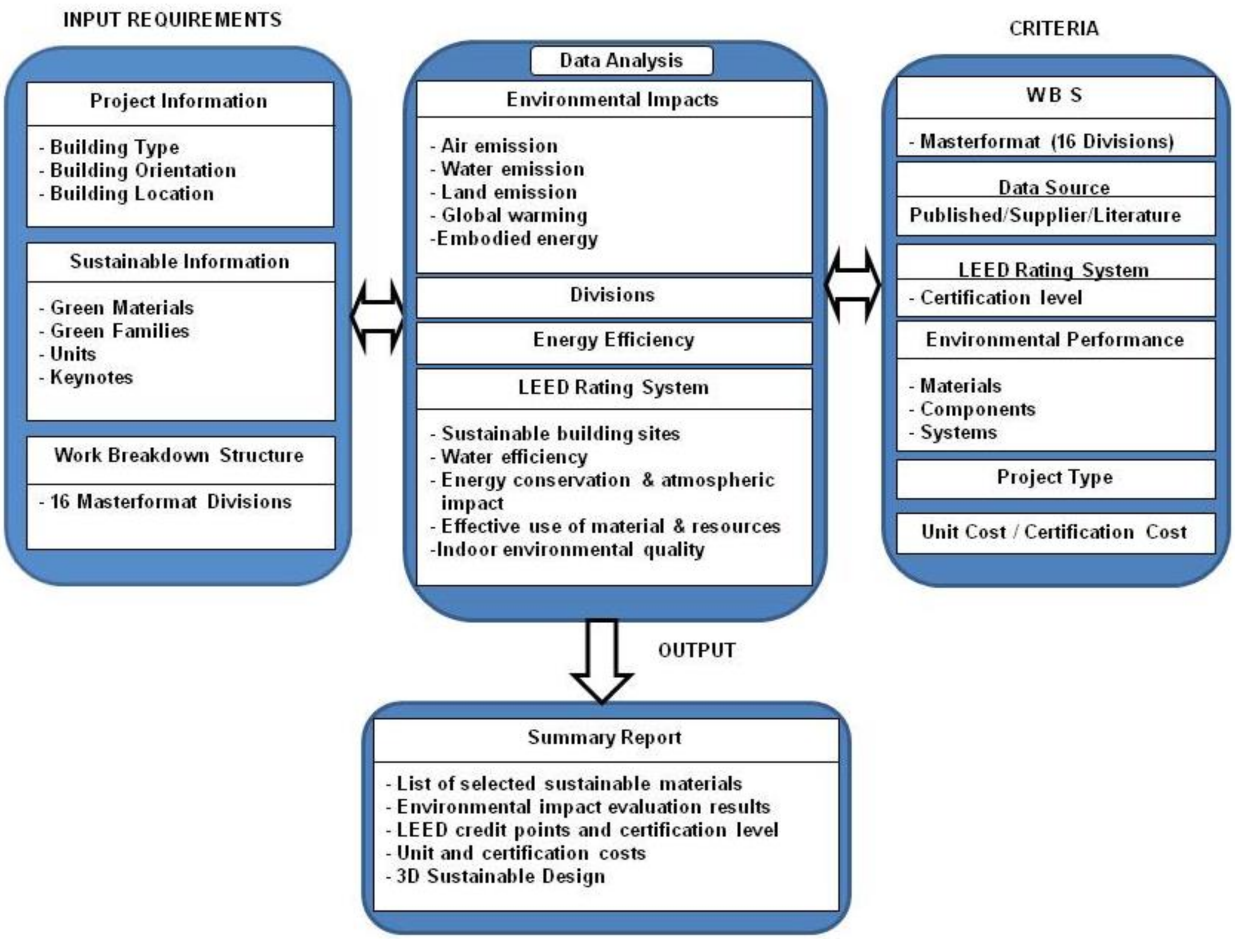

Figure 4. 2. Figure 2 Model Architecture

4.5. Model Development Process

Since the model incorporates four different phases, its development is implemented sequentially, as described in the following sections.

4.5.1. Model Database (Phase 1)

The basis of a methodology, which simplifies the process of establishing sustainable design for proposed building projects in an efficient way, incorporates the importance of instant access to the data needed.

4.5.1.1. Design and Development

The design and development of the databases are accomplished in two steps: these being conceptual modelling, and implementation of the model. First, problem investigation and user needs are acknowledged based on the literature review. Then, the database requirements are identified and the conceptual design is carried out. Second, the data model implementation concentrates on the transformation process from conceptual to logical design. Thereafter the physical design starts by creating a list of related tables to store the collected data. These tables are based on the applied WBS. The process of choosing green materials from the collected data and storing them in the database is shown in Figure 4.3. The data related to the green materials is saved as family files, which can be identified by the BIM tool. Thus, in the external sustainable database, up to 3,000 families are collected and are arranged based on the 16 Masterformat divisions where various types of information such as details about the material used, suppliers' contact data, assigned keynote, potential certification points, and assembly codes are stored.

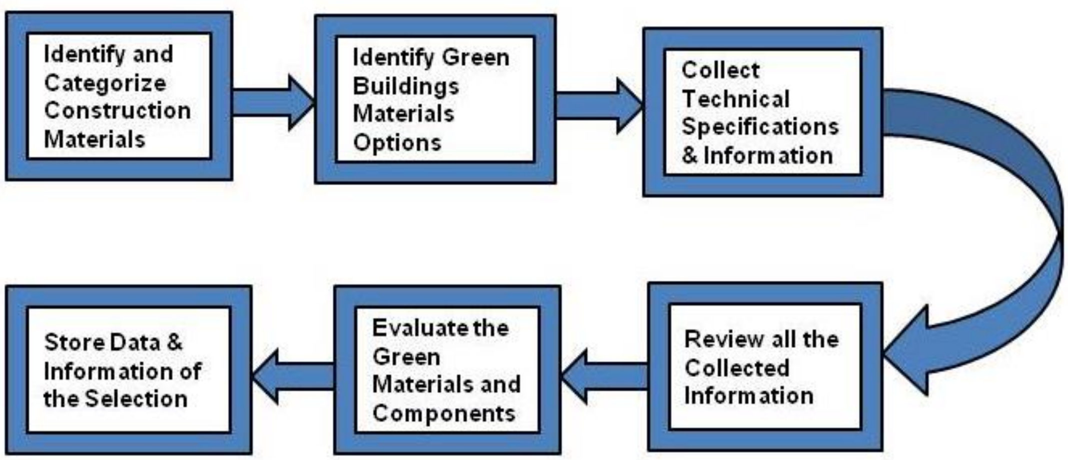

Figure 4. 3. Processes of selecting and storing green materials

4.5.2. 3D (BIM) Module (Phase 2)

This phase focuses on customizing BIM's tool to fit the modularity requirements of the model. The first step is to design and implement a 3D module capable of storing newly created and added families and keynotes for components employed in residential buildings by using certified green materials. The module is linked to the database developed in the aforementioned phase 1).

To simplify the development process of this module, a flow chart is created as shown in Figure 4.4.

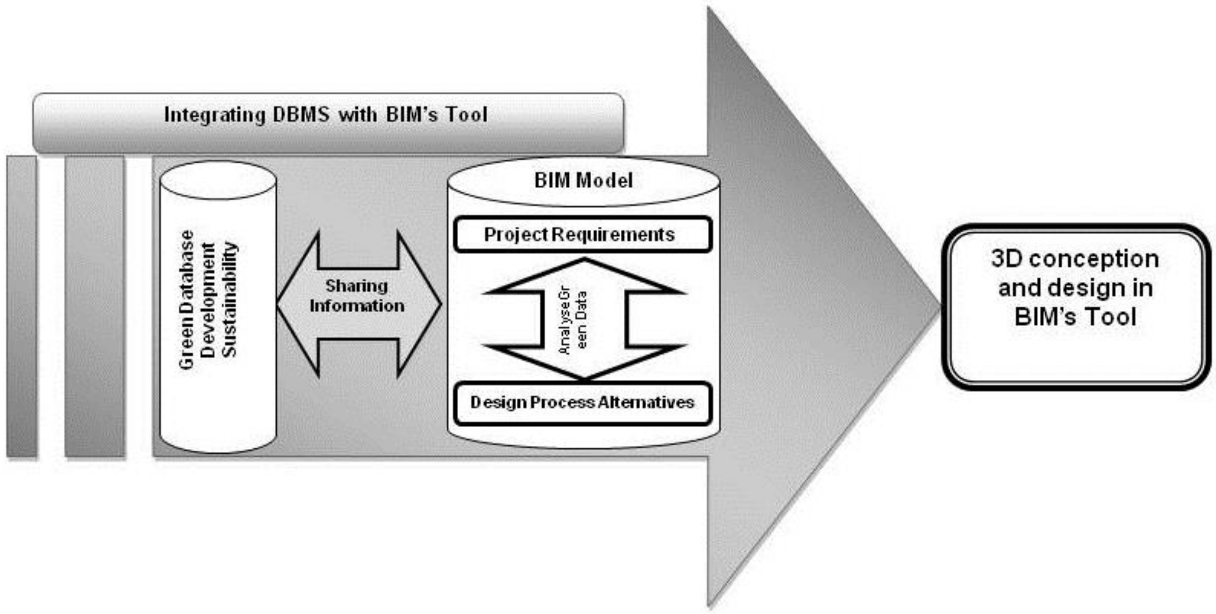

Figure 4. 4. Process of integrating database management system with BIM for sustainability

An efficient coding system is the main aspect that represents the relationship between the stored data. Therefore, it is important to select a unique code for each item that is presented in a separate line in the database. The coding system allows users to accelerate the process of retrieving necessary information. A five-digit number representing the division, subdivision, elements, and material names is used to store the collected data. Creating the families is based on modifying the inherited resources by adding new parameters. Customizing and duplicating an existing family adds an important feature to the model. For instance, the families built in BIM's tool consist of different types such as walls, floors, stairs, windows, and doors.

4.5.3. LCA Module (Phase 3)

This phase concentrates on designing and implementing an LCA module that is linked to an external database, which in turn is associated with BIM's module to store the extracted quantities from the 3D design and to evaluate their EIs. The extracted bill of quantity is linked to ATHENA® Impact Estimator© via a text file exchange way. Authors elected to use ATHENA Impact Estimator for Buildings because it is a common tool used by the North American construction industry. It is designed to evaluate whole buildings and assemblies based on internationally recognized life cycle assessment (LCA) methodology. This is an important step because LCA analysis outlines how the EIs of all products should be documented and communicated to the owner. Hoff (2008) considers that ISO 14020 calls for the implementation of a standardized format for communicating product EI, called Environmental Product Declaration (EPD). Therefore, LCA should be applied to integrated systems in a building by combining all the EPDs of every selected component in a single EI assessment. This paper focuses on analyzing the EIs of architectural and structural systems used in the 3D design that are ranked according to their awarded certification points. To ease the development process of this module a framework is created as illustrated in Figure 5.5.

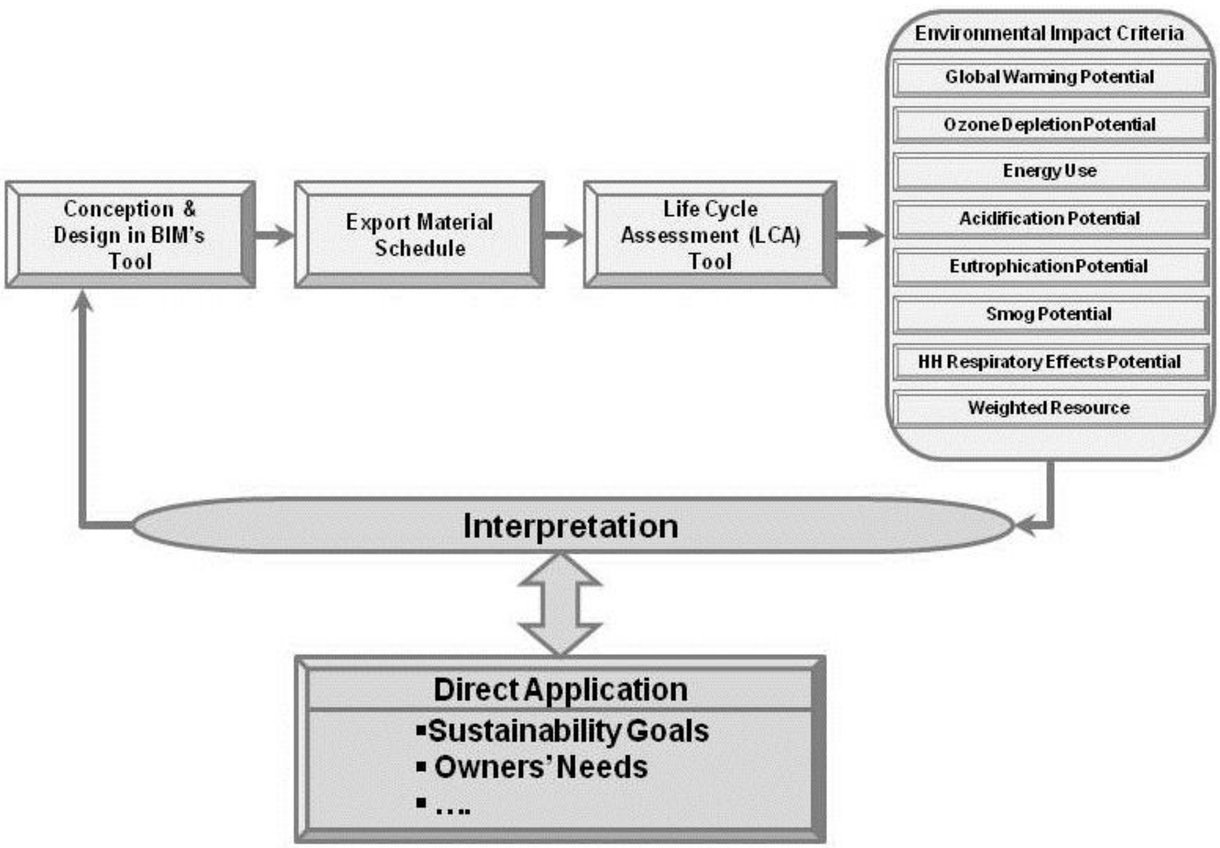

Figure 4. 5.Fraamework for integrating BIM and LCA tools

4.5.4. Green certification Module (Phase 4)

This phase consists of designing a certification and cost module linked with the other two modules, as explained in Figure 4.6. By organizing the data collected from the suppliers and publishers - which are provided in the BIM and LCA modules - it will be possible to link them to this module in order to collect potential certification points and identify the certification level of the designed building. Authors collected information about sustainable materials and components from the manufacturers' and vendors' websites. Included in this information are the potential LEED points that can be gained if these materials or components are used in the design. This information is stored in a database linked to the families of the BIM's tool. Therefore, when designers design 3D models for proposed building projects and select any of these sustainable materials or components, the LEED points potentially gained by these selected items are identified and stored in the schedule associated with the model. Afterwards, users can add up these LEED points to identify the potential number that the proposed building can earn. Furthermore, the associated cost will be generated by linking the BIM module with the cost database for green and certified materials.

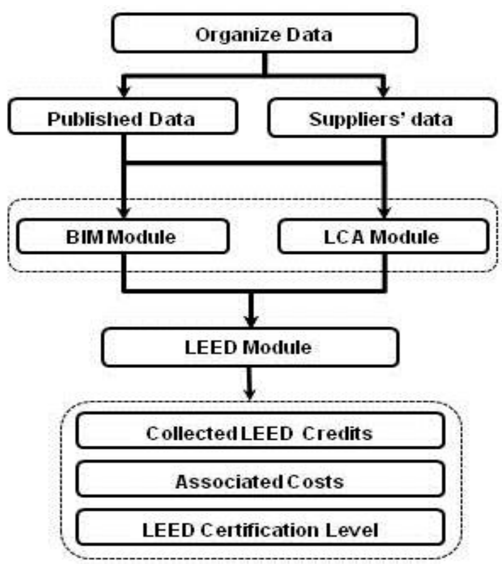

Figure 4. 6. LEED module data flow diagram

USGBC allows LCA to immediately impact LEED credits for projects using building materials which have been assessed and rated by specific third-party organizations to be eligible for immediate "Innovation in Design" credits under the current certification standard (Hoff, 2008). Some of the data collected from the suppliers' webpages includes certification points, which can be potentially earned.

The development of the model described in this paper aims to present a Database Management System containing information about green and certified materials used to create families and keynotes and to link them to the BIM's tool to enable users to design 3D sustainable building models at the conceptual stage of a project's life. It takes into consideration the process of connecting the output of BIM with different modules such as LCA, Green Certification System and associated cost. The developed model shows how a variety of information about sustainable buildings can be integrated at their conceptual design stage to be used by owners and designers.

4.6. Testing and Validation

The preceding paragraphs explored in detail the methodology followed in developing the integrated model. This section validates the capabilities of the model. Its performance is examined through the designing a 3D model for an actual six floor apartment building project, which is currently at the design stage in the city of Ottawa. The proposed construction land has an area of 7,500 ft^2 and the building consists of six units, one on each floor with an area of 1,610 ft^2 per floor for a total gross area of 9,660 ft^2 and a perimeter of 180 ft. The case example is used to test the workability of the integrated model. Authors created a 3D conceptual design of the current project where its associated sustainable components and materials were selected from the developed database. The components used in the design of the case example had their specifications as close as possible to the ones used in the real design. Every component, such as floor, wall, roof, and window has its associated LEED information linked to the families of the BIM tool, which includes the manufacturers' web pages and contact information.

Using the developed model to design the new building project in the city of Ottawa shows that owners and designers are provided with a vital tool that helps them when they decide to select green components based on what is introduced in the model as they can automatically see potentially earned LEED points, LCA and cost results during the conceptual design process.

Figure 4.7 shows a rendered snapshot of the proposed green building, which is designed based on the development processes described previously. The process is implemented in three steps.

Figure 4. 7. Snapshot of the designed building with its green families

4.6.1. 3D Conceptual Sustainable Design (Step 1)

A 3D design of the building is executed using Autodesk Revit Architecture©. With the established keynotes and created green families, the sustainable design for the building is fulfilled. First, the user has to link the green keynote file to the current building model by uploading and attaching it to the design as shown in Figure 4.8.

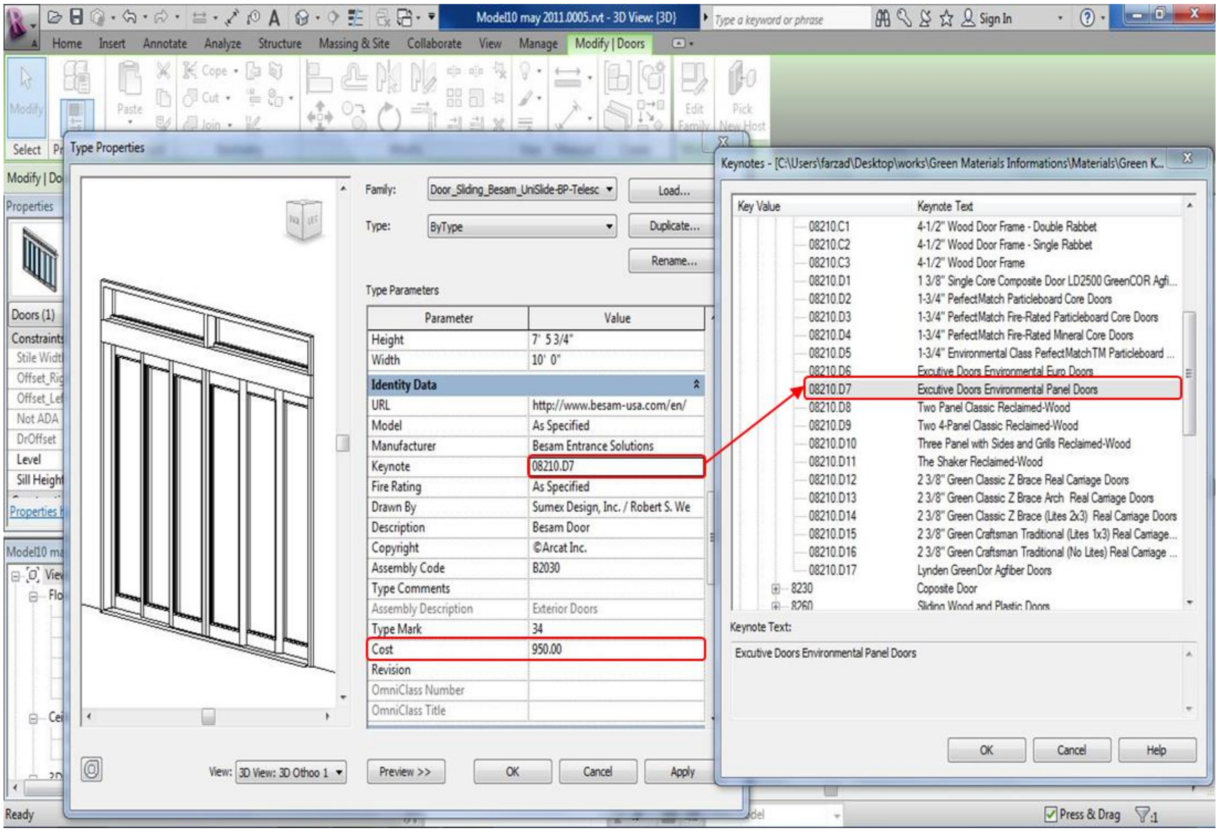

Figure 4. 8. A snapshot of the keynote in Revit

By using the new keynotes, users have the option of selecting the most appropriate type of certified materials: for example the selection of a composite window instead of a single one. Furthermore, users are provided with the unit cost where applicable. As explained in phase 4, the external green database contains detailed stores of information such as URL addresses for every family. As illustrated in figure 4.9, by clicking the family window used in the model, the user can access the information about the certification and the potential earned points of that family as claimed by its supplier. More than 90% of the components and families used in the case example have LEED certification points, which are provided by their manufacturers and stored in the BIM's database.

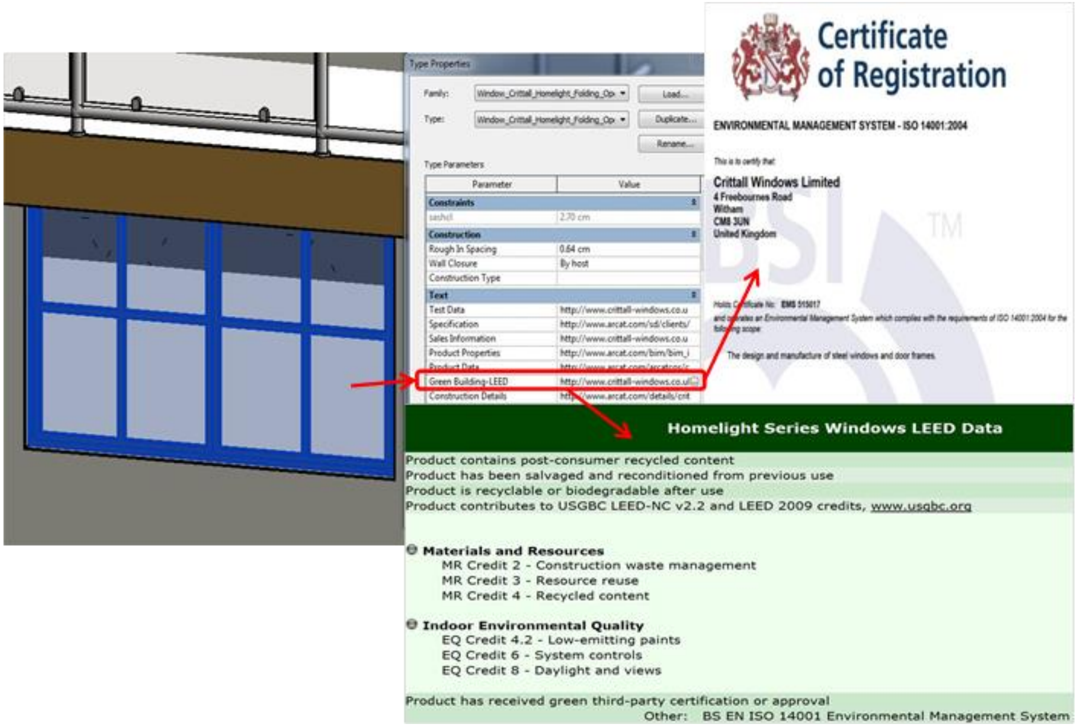

Figure 4. 9. A snapshot of LEED information which is stored in external BIM database

Moreover, users can extract the materials' bill of quantities and export them to an external database which is linked to the LCA module to implement necessary assessment of the EIs as shown in Figure 4.10.

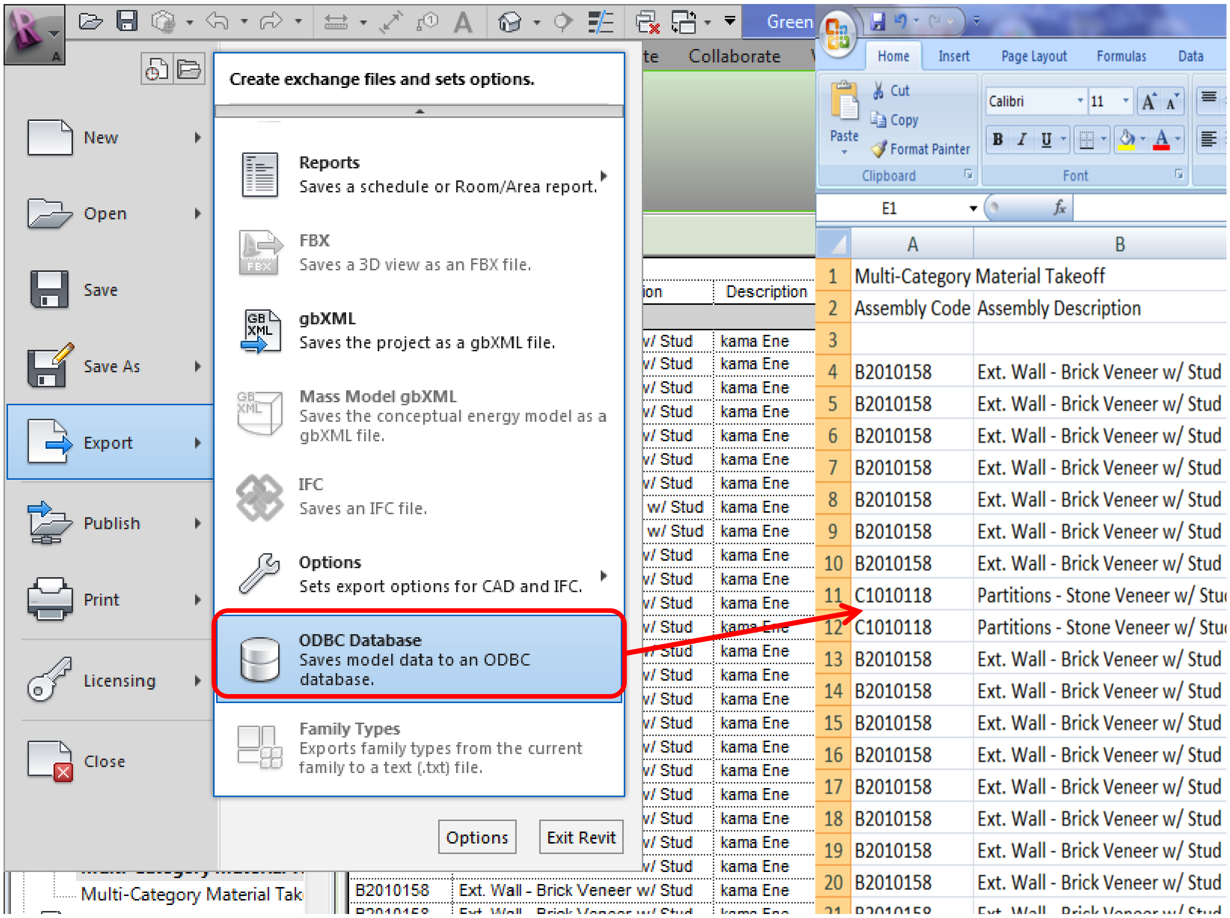

Figure 4. 10. Exporting materials' bill of quantity to the external database

Table 4.1 shows selected components based on the functional, technical, and financial specifications of sustainable 3D families collected from manufacturers' web pages. Furthermore, it shows the most applicable criteria for those elements boasting environmentally friendly capabilities. The provided information shows that the selected materials used in creating sustainable 3D families meet the functional, technical, and financial specifications and take into consideration the environmentally friendly aspects.

The data provided in the functional part illustrates the capability of the materials used to provide an overall satisfaction for owners and engineers by achieving the sustainable design objectives.

Generally, manufacturers provide several technical specifications for each component and family, but the ones shown in Table 4.1 is information related to the sustainable design factors. In reference to the financial element, the specifications shown are related to the cost of the selected components.

Table 4.1. Functional, technical and financial specification of sustainable materials used in the 3D BIM Model

Green Families used in the BIM's sustainable model	Windows	Roofing Systems	Floor	Wall	Door
Functional Criteria	-Recyclable packaging materials, -products are certified by Scientific Certification Systems (SCS) to contain pre-consumer recycled content, which includes glass cullet and wood fiber in Fibrex® material, -The recycled content certified to retain Forest Stewardship Council (FSC) Chain-of-Custody certification (SCS-COC-001337) for pine wood-based components.	-To divert construction and demolition debris from landfills and incineration facilities. -Redirect recyclable resources back into the manufacturing process. -Redirect reusable materials to appropriate sites. - Use materials with recycled content such that post-consumer plus ½ pre-consumer is at least 10% or 20%. - Use building materials or products that have been extracted, harvested or recovered, as well as manufactured, within 500 miles of the site for a minimum of 10% or 20% - Use rapidly renewable building materials and products for 2.5% of the total value of all building materials - Patented Fibrex® material provides the strength of wood, low cost of vinyl	- Resource Reuse - Recycled Content - Regional Materials - Use rapidly renewable building materials and products (made from plants that are typically harvested within a ten-year cycle or shorter) for 5% of the total value of all building materials and products used in the project	- Framing, Off-Site Fabrication of the structural systems. - utilize proprietary fabrication techniques for limiting waste in a controlled factory environment. - enables resource efficiencies that can often eliminate on-site waste, - reduced assembly time and smaller construction crew, - Environmental Preferable Products, - All EPS utilized is Green Guard® certified and therefore have lower emissions of VOCs, which helps reduce a home's contribution to smog compared to earlier EPS foam products. - reduce a home's contribution to smog compared to earlier EPS foam products -Reduction in assembly time and call backs and the predictability and adherence to project scheduling provided by indoor fabrication.	- No Added Urea Formaldehyde requirement, - Constructed of Recycled- content materials and contain insulating core material that does not contribute to ozone depletion. - Factory applied finishing is applied based on control of volatile organic compounds (VOC) emissions. -Regional Manufacturing (500 miles) -Rapidly Renewable (Bamboo veneer)

Technical Specifications	-Exposure Category: 2000 (pa) - Air Permeability: Not more than $16m^3$/h/m joint, : 300 (Pa) -Water tightness: no leakage: 200 (Pa) - Wind Resistance: no damage & only permissible deflection: 2000(Pa) -Design testing, manufacture and installation carried out under Quality Management Systems certified to BS EN ISO 9001.	- asphalt shingles, Thermoplastic polyolefin (TPO) and Poly-Vinyl Chloride(PVC)membranes, Ethylene Propylene Diene Monomer(EPDM) membranes, poly Iso insulation, extruded or expanded polystyrene insulation, gypsum board, mineral fiber board, ballast, metal flashings, metal roof panels, and clean wood. - Reuse or salvage of ballast, Energy Guard™ roof insulation, and membrane - Material diverted from the waste stream during the manufacturing process, - Materials considered being an agricultural product, both fiber and animal, that takes 10 years or less to grow or raise, and to harvest in an ongoing and sustainable fashion. - Low-E glass for energy efficient performance - Folding hardware won't interfere with window treatments	- Maintain 100% of Shell/Structure and 50% in addition to Non-Shell/Non-Structure Green Floors can redeye your old carpet making it look like new. We can also refurbish your carpet floor tiles. - Divert 50% From Landfill Green Floors specialists can analyze the carpet in the building -10% (post-consumer + 1/2 post-industrial) -20% manufactured regionally	- the system allows for construction waste per home built being less than 2.5 pounds (or 0.016 cubic yards) or less of net waste per square foot of conditioned floor area. -contain recycled content at a minimum of 25% postconsumer and 50% post-industrial for at least 90% of the building component.	-Rigid foam plastics and fiberglass are typically used as insulation core, -Interior doors are typically constructed of wood products (veneer, core materials, and styles) and synthetic wood products (plastics),
Financial Investments	Minimise disturbance of the existing structure and internal finishes to a minimum, thereby reducing the cost of making good.	This roof was selected because of its engineered cooling attributes for a cooler roof and a projected cooling cost saving of 20%.	lowers maintenance costs a minimum of 10% (based on cost) of the total material value	Benefits accrue well beyond the design and construction budget through energy savings, a reduction in the contributory costs of the built environment to global warming	The cost is higher than for conventional doors. Such cost increases are dependent on the sustainable features specified.

4.6.2. Assessing the Design's Environmental Impacts (Step 2)

Once the design is finished the building is assessed and analyzed based on the sustainability requirements using the LCA module and its associated tool ATHENA® Impact Estimator©. This user-friendly tool provides quick results in the form of tables and graphs. The Impact Estimator allows users to change the design, substitute materials, and make side–by–side comparisons. It also lets users compare similar projects with different floor areas on a unit floor area basis.

First, users input the necessary information such as geographic location, building life and occupancy/type, and, if desired, annual operating energy values into ATHENA. Second, the exported bill of quantities extracted in step 1 is imported as text exchange file into ATHENA® Impact Estimator©. Pre-set dialogue boxes prompt users to describe the different assemblies, such as entering the width, span, and live load of a floor assembly.

It is worth mentioning that this software has some limited options for each assembly. An example of this is that it is necessary to select materials from the Athena library that have specifications close to the ones used in the BIM model. While the Impact Estimator offers a wide array of material and assembly combinations, the user needs to enhance the project design with additional materials. It should be noted that when it is decided to add "Extra Basic Materials", the application doesn't know how or where these materials are to be added and used. Hence, the LCA profile provided for extra basic materials is diminished in the sense that the application delivers the material to the building site, but does not calculate any effects associated with the usage of this material. For instance, using the formerly mentioned case as an example, softwood lumber, which is a green material and is used in different parts of the building, is added beside other assembly groups as extra basic materials.

After entering all the necessary information, Impact Estimator provides series of reports in terms of: 1) Primary Energy Consumption, 2) Acidification Potential 3) Global Warming Potential, 4) Human Health (HH) Respiratory Effects Potential, 5) Ozone Depletion Potential, 6) Photochemical Smog Potential, 7) Eutrophication Potential, 8) Weighted Raw Resource Use, which are the focus of this case example. Figure 4.11 represents samples of the bar chart reports extracted from ATHENA® Impact Estimator©. As shown in Figure 5.11, beams and columns, as well as walls consume fossil fuel more than other assembly groups (600,000 MJ and 700,000 MJ, respectively). Roofs and foundation use about 480,000 (MJ) of fossil fuel consumption. Conversely, when it comes to Ozone depletion, walls, with 6E (-5) (Kg CFC), and foundation, with 5E (-5) (Kg CFC), are two groups with noticeable amounts. Meanwhile, floors and roofs are similar, both having 3.5E (-5) (Kg CFC). Walls, on the other hand, seem to have the most smog potential with around 250 (Kg No^x) out of the total amount, which is 720 (Kg No^x). Walls create the highest amount of Global Warming potential, averaging around 60,000 (Kg Co2), followed by the foundation, with 40,000 (Kg Co2). Foundation, roofs, beams and columns produce similar amount of acidification potential, usually around 17,000 (moles of H+), whereas walls produce much more than the others with around 35,000 (moles of H+). Similarly, the HH Respiratory effects for walls have the most effects, averaging around 320 out of a total of 700 (Kg PM2.5). In the ultimate interpretation among the selected components, walls have the most impact on the environment in comparison with other assembly groups. Two reasons for this can be described here. The former is that walls are in direct contact with the outdoor environment while having several openings (wants and voids) and the various layers of walls are not made from sustainable materials based on the information provided by the supplier. The latter reason is that all the green materials stored in the BIM's model and its associated library is not supported by ATHENA®

Impact Estimator©. The results provided by ATHENA® Impact Estimator© represent an appropriate overview about the EI of the design.

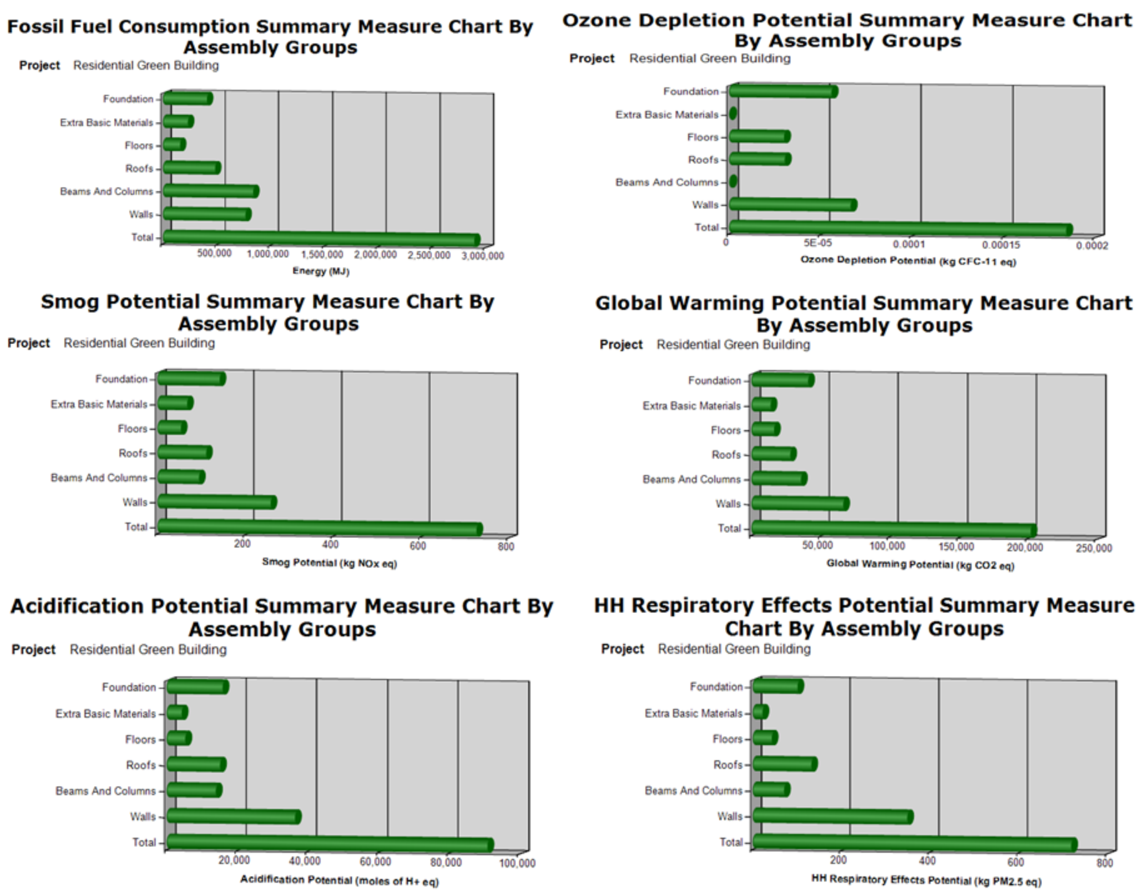

Figure 4. 11. Environmental Impact sample report of the implemented design

Based on the LCA reports, designers are able to identify the environmental impacts of the materials used in the design and decide on the ones that best fit the project's sustainable goals at its conceptual stage. Users, however, may identify the number of points gained by using the LEED and Cost module, which is linked to the other two modules.

5.6.3. Identifying the Potential LEED Points Earned and Associated Cost (Step 3)

In this step we identify the points earned by the 3D design based on the LEED-RS. Table 4.2 lists information related to the collected materials and the potential points that can be earned from them as well as the actual points earned by the design of step 1. As it is shown, the designed 3D model gets 54 LEED points and stands for a Silver level based on the CaGBC rating system. This number of LEED points is approximate since the focus of this study is at the conceptual design stage, therefore the calculated points do not reflect the final number that can be earned when the building is consummated. The intent is to just provide owners and designers with an idea about the potential LEED points that the proposed building may earn if a decision is made to continue the project. At the conceptual stage, owners and designers do not have detailed information about the project. This integration will give them an approximate idea allowing them to realize the potential LEED points the designed 3D model can earn them.

Table 4. 2. Potential and actual LEED points that can be / are earned by the model

LEED-NC Credits that can be earned by each family and assembly groups using BIM-based performance analysis software			Roof		Floor		Windows		Doors		Wall		Beam& Column		Spiral Stairs& Railing	
LEED Credit	**Credit Description**	**LEED Points**	PEP[x]	EPM[xx]	PEP	EPM	PEP	EPM	PEP	EPM	PEP	EPM	PEP	EPM	PEP	EPM
Sustainable Sites																
SSp1	Construction Activity Pollution Prevention	Required														
SSc1	Site Selection	1														
SSc2	Development Density and Community Connectivity	3,5														
SSc3	Brownfield Redevelopment	1														
SSc4.1	Public Transportation Access	3,6														
SSc4.2	Bicycle Storage and Changing Rooms	1														
SSc4.3	Low-Emitting and Fuel-Efficient Vehicles	3														
SSc4.4	Parking Capacity	2														
SSc5.1	Protect and Restore Habitat	1	*	1 point							*	1 point				
SSc5.2	Maximize Open Space	1	*								*					
SSc6.1	Stormwater Design: Quantity Control	1	*	1 point												
SSc6.2	Stormwater Design: Quality Control	1	*													
SSc7.1	Heat Island Effect: Non-Roof	1	*													
SSc7.2	Heat Island Effect: Roof	1	*	1 point												
SSc8	Light Pollution Reduction	1														
Water Efficiency																
WEp1	Water Use Reduction	Required														
WEc1	Water Efficient Landscaping	2,4														
WEc2	Innovative Wastewater Technologies	2														
WEc3	Water Use Reduction	2-4														
Energy & Atmosphere																
EAp1	Fundamental Commissioning of Building Energy															
EAp2	Systems	Required														
EAp3	Minimum Energy Performance	Required					*	1 point								
EAc1	Fundamental Refrigerant Management	Required														
EAc2	Optimize Energy Performance	1-19	*	6 point			*	8 point			*	10 pt				
EAc3	On-Site Renewable Energy	1-7														
EAc4	Enhanced Commissioning	2	*	1 point			*	1 point								
EAc5	Enhanced Refrigerant Management	2									*	1 point				
EAc6	Measurement and Verification	3									*					
	Green Power	2														
Materials & Resources																
MRp1	Storage and Collection of Recyclables	Required														
MRc1	Building Reuse: Maintain Existing Walls, Floors, Roof	1-5									*	1 point 1 point				
MRc2	Construction Waste Management	1-2	*	1 point			*	1 point			*					
MRc3	Materials Reuse	1	*								*					
MRc4	Recycled Content	1-2	*	1 point	*	1point	*		*	1 point			*	1 point	*	1point
MRc5	Regional Materials	1-2	*	1 point	*	1point	*	1 point	*				*	1 point	*	
MRc6	Certified Wood	1					*	1 point	*							
Indoor Environmental Quality																
EQp1	**Minimum Indoor Air Quality (IAQ) Performance**	Required					*									
Required		Required														
EQp2	**Environmental Tobacco Smoke (ETS) Control**	1									*	1 point				
Required		1					*									
EQc1	**Outdoor Air Delivery Monitoring**	1									*	1 point				
EQc2	**Increased Ventilation**	1	*	1 point	*	1point	*	1 point								
EQc3	**Construction IAQ Management Plan: During**	1					*								*	1point
Construction		1			*											
EQc4.1	**Low-Emitting Materials: Adhesives and Sealants**	1					*	1 point	*	1 point						
EQc4.2	**Low-Emitting Materials: Paints and Coatings**	1														
EQc4.3	**Low-Emitting Materials: Flooring Systems**	1					*	1 point								
EQc4.4	**Low-Emitting Materials: Composite Wood and**	1					*									
Agrifibre		1					*	1 point								
EQc5	**Indoor Chemical and Pollutant Source Control**	1					*									
EQc6	**Controllability of System: Thermal Comfort**															
EQc7	**Thermal Comfort: Design**															
EQc8.1	**Daylight and Views: Daylight**															
EQc8.2	**Daylight and Views: Views**															
Innovation & Design Process																
IDc1	**Innovation in Design**	1-5									*	1 point				
IDc2	**Accredited Professional**	1									*					
Regional Priority																
RPc1	Durable Building	1					*	1 point			*	1 point				
RPc2	Regional Priority Credit	1-3									*					

Table 4.3 shows a sample of the costs of the selected materials based on R.S. Means data. In this table the total estimated cost of each family is calculated using R.S. Means Green Building Cost database. In this database the unit cost of each family is calculated based on the national average value for the year 2012 and adjusted for the city of Ottawa. To prepare the cost estimate, materials with similar specifications as to the quantity take off extracted from the developed 3D-BIM design, which are selected from R.S. Means database.

Table 4. 3. Associated cost of the selected components based on R.S. Means cost data

Description	Unit	Quantity	Material ($)	Labor ($)	Total Unit Cost ($)	Total Item Cost ($)
Windows						
Windows, vinyl double hung, grids, low E, J fin, 37" x 69", including grill, J finish, low E, extension jambs	Ea.	5	$ 262.00	$ 44.0	$306.00	$ 1530
Windows, wood, casement, vinyl clad, premium, double insulated glass, multiple leaf units, double unit, 3'-4" x 3'-0" high, incl. frame, screens and grilles	Ea.	18	$ 430.00	$ 59.0	$ 489.00	$ 8802
Windows, wood, casement, vinyl clad, premium, double insulated glass, 2'-0" x 6'-0" high, incl. frame, screens and grilles	Ea.	6	$ 375.00	$ 44.0	$ 419.00	$ 2514
Roof						
Wood shingles, white cedar, 3/4" thick x 16" long, 5" exposure on roof	Sq.	27.41	$ 154.00	$147.0	$301.00	$ 8250
Floor						
Resilient Flooring, cork tile, standard finish, 5/16" thick	S.F.	18,820	$ 8.60	$1.04	$9.64	$ 181,425
Doors						
Doors, wood, residential, exterior, combination storm and screen, pine, cross buck, 7'-1" x 3'-0" wide	Ea.	1	$ 330.00	$78.5	$408.5	$ 408.5
Doors, wood, residential, entrance, flush, birch, solid core, 1-3/4" x 7'-0" x 2'-4" wide	Ea.	30	$ 111.00	$44.0	$155.00	$ 4650
Column						
Column, structural, mild steel scrollwork, flat, stock unit, plain, painted, 9" W, shop fabricated	V.L.F.	870	$ 9.15	$9.95	$19.86	$ 17,278
Railing & Stairs						
Railing, ornamental, bronze or stainless, 3'-6" high, posts @ 6' O.C., hand-forged, plain	L.F.	907.1	$ 101.00	$33.0	$134.00	$ 121,538

4.7. Conclusion and future research

This paper presents a methodology for modeling the procedures of implementing sustainable design for building projects at their conceptual stage by integrating BIM, LCA and relational databases with a workable model. The model includes a 3D (BIM) module, an LCA module and a LEED and Cost module. The databases of the model are based on collected data from the literature, suppliers, publishers, CaGBC, and USGBC websites. The developed model is intended to assist owners, architects and engineers in accomplishing conceptual sustainable design for building projects and measuring their environmental impacts at early stages. Furthermore, the model allows users to identify the earned points based on the LEED-RS. The model is a simple and user-friendly where user inputs and error prediction are minimized. Time reduction, fast calculations, and professional output reports are some of its advantages. The major limitation of the proposed model is that it cannot be applied at the detailed design stage of a building project because its integrated database stores information only for components that are commonly used in building projects. Furthermore, the developed database has been designed based on couple of collected BIM files which contain limited number of certified components, all of which are designed and provided by manufacturer companies. This is a limitation for the model because it does not cover all the existing green elements. This means that there are several green families that require being designed and converted to BIM format files and added to the database. Moreover, the proposed model is not fully automated; users still have to do some manual steps such as linking the database directly without importing or loading the green materials, linking the model's information with LCA tools to execute LCA, and cost estimate calculations. The research in this domain is ongoing, and its authors are currently engaged on enhancing the databases linked to the developed model in addition to achieving a full automated integration between different tools needed to take part in sustainable conceptual design for building projects.

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CHAPTER 5

TECHNICAL PAPER II

Integrating Building Information Modeling (BIM) and Energy Analysis Tools with Green Building Certification System to Conceptually Design Sustainable Buildings

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Abstract: It is commonly known that the energy consumption of buildings is quite high; therefore, owners, architects, and engineers should be more concerned about the sustainability and energy performance of proposed building projects. For years, energy analysis tools have been used by designers to design energy-efficient buildings. Generally, the energy analysis for this type of facilities is mostly conducted at the end of the design stage, once their components and elements have already been selected. However, analyzing the energy consumption of those components at the conceptual design stage is very helpful for designers when making decisions related to the selection of the most suitable design alternative that will lead to an energy-efficient building. Building Information Modeling (BIM) has the capability to help users assess different design alternatives and select vital energy strategies and systems at the conceptual design stage of proposed projects. Furthermore, by using BIM tools, designers are able to select the right type of materials early during the design stage and to make energy-related decisions that have great impact on the whole building life cycle.

The main objective of this paper is to propose an integrated methodology that links BIM and energy analysis tools with green building certification systems. This methodology will be applied at the early design stage of a project's life. It will help designers measure and identify potential loss or gain of energy for different design alternatives and calculate the potential LEED points they may accumulate and gain and accordingly select the best one. An actual building project will be used to illustrate the workability and capability of the proposed methodology.

KEYWORDS: BIM, Energy Analysis and simulation, Green Building, Certification System, LEED, Sustainable Design.

5.1. INTRODUCTION

Important decisions related to the design of sustainable buildings are made at the conceptual stage of the building life cycle. Energy analysis is typically performed after the architectural/engineering design and related documents have been produced. Schueter and Thessling (2009) think that this practice does not consider the importance of linking the design and energy analysis processes during early stages and yet it leads to an inefficient way of backtracking to modify the design in order to achieve a set of performance criteria. Sartori and Hestnes (2007) claim that buildings demand energy in their life cycles, both directly and indirectly: directly for their construction through operating, rehabilitation and eventually demolition (operating energy); indirectly through the production and installation of the materials they are made of (embodied energy). Thus, one of the emphases of this study is on evaluating and analysing the energy (embodied and operating) of building projects during the conceptual design stage of their life cycles.

Energy efficiency is an important feature in labeling building materials as being environmentally friendly. The goal in using energy-efficient materials is to reduce the amount of artificially generated power that must be brought to a building site (Jong et al., 2010). Generally, building materials consume energy throughout their life cycle starting at the manufacturing stage, passing through that of use, and finishing during the deconstruction stage. These stages include raw material extraction, transport, manufacture, assembly, installation as well as disassembly, deconstruction, and decomposition.

Presently, Building Information Modeling (BIM) tools have the option to provide users with an opportunity to explore different energy saving alternatives early in the design stage, thus avoiding the time-consuming process of re-entering all the building geometry and other supporting information necessary to complete the energy analysis.

The use of BIM tools may help owners and designers make energy-related decisions that have high impact on the life cycle cost of proposed building early of its design stage. Furthermore, integrating BIM with Life Cycle Assessment (LCA) tools at that stage would help designers select components and materials that have lower embodied energy. In most building projects, materials and components are evaluated and selected based on functional, technical, and financial criteria. A clear understanding of the functional criterion of the building materials is essential to ensure the success of a project. It is known that a building project functions successfully only when its design satisfies the emotional, cognitive and cultural needs of the people who use it (WBDG, 2012). Technical specifications provide detailed information about the materials and components used in a building. Usually, such information, which is provided by the manufacturer, contains information about the type, size/dimensions, installation procedures, and other information that show the capabilities and applications of these materials. In order to meet the requirements of a cost-effective design for proposed buildings, the financial criterion of the selected materials should also be taken into consideration. At the present time, environmental impact is gaining priority within the process of selecting construction materials. Technically, construction materials should satisfy strength, serviceability and architectural requirements without having a negative impact on the environment (Somayaji, 2001).

Usually, using BIM tools to design sustainable buildings necessitates the selection of materials and systems whose embodied energy can easily be evaluated. Thus, the common method used to quantify the embodied energy of the selected materials is LCA, which is a concept used to evaluate environmental concerns (Khasreen et al., 2009). For this purpose, designers use LCA tools to model, to modify, and to input energy simulation results and calculate the operating and embodied effects of their design. Hence, it will be necessary to evaluate and to compare the capabilities of different methods of exchanging information between BIM and LCA tools, which are highly important for designers who need to transfer the design information directly from the BIM model to the energy analysis software. Schema such as the Industry Foundation Classes (IFC) data model that is the standard data specification for exchanging information throughout the entire lifecycle of a building (ISO/TC 184/SC 4, 2005) and Extensible Markup Languages (XML), which defines a set of rules for encoding documents in a human-readable and machine-readable format, are currently promoted by various groups in the construction industry. This paper will also focus on analysing the day lighting and measuring the thermal gain / loss of proposed buildings at their conceptual design stage. Using the proposed methodology at the conceptual stage of the project will help designers determine the products that best meet their needs, evaluate the sustainability of the building based on selected rating systems, and visualize the energy and lighting analysis results in an easy, quick, and convenient way.

5.2. LITERATURE REVIEW

The impact of BIM on design practice is significant due to the fact that it raises new ways and processes of delivering designs, construction, and facilities management services. Owners are not only demanding buildings to be designed and delivered on time, cost efficiently, and with high quality but are also demanding services beyond design and construction (Clayton et al, 1999). Based on Kubba (2012) and Becerik-Gerber and Rice (2010), development of a schematic model prior to the generation of a detailed building model, allows the designer to make a more accurate assessment of the proposed scheme and to evaluate whether it meets the functional and sustainable requirements set out by the owner; this helps increase project performance and overall quality. The advent of BIM along with the emergence of global challenging issues like sustainability, and life cycle cost of buildings, necessitates designers to incorporate the basic performance analysis from an early design phase. Those performance analyses are special quality analysis, energy performance, social impact and environmental performance into its framework by further developing the concept of virtual space and virtual building (Kam et al, 2004). An integrated BIM system can facilitate collaboration and communication processes between project participants in an early design phase to effectively provide a well-performing building during operations (Hungu, 2013). BIM allows multidisciplinary information to be superimposed within one model by incorporating structural, mechanical, electrical, plumbing and lighting information into a single model (Tucker and Newton, 2009). It helps owners visualize the spatial organization of the building as well as understand the sequence of construction activities and the project duration (Eastman et al, 2008). Combining sustainable design strategies with BIM technology has the potential to change traditional design practices and to efficiently produce high-performance designs for proposed buildings. BIM technology can be used to support the design and analysis of a building system at the early design phase. This includes the experimental structural analysis, the environmental controls, the construction method, the selection of new materials and systems and the detailed analysis of the design processes.

For the past 50 years, a variety of building energy simulations and analysis tools have been developed, enhanced and applied by the building industry. Examples of these tools are BLAST, EnergyPlus, eQUEST, TRACE, DOE2, Ecotect and Integrated Environmental Solution (IES-VE) (Crawley et al, 2005). Grobler (2005) claimed that building designs (conceptual and detailed) affect the construction and operation costs of a building. Several researchers describe energy analysis as a holistic evaluation (Abaza, 2008; Dahl et al, 2005; Lam et al, 2004). They claim that decisions made early in a project have a strong effect on the life cycle costs of a building. BIM has received tremendous interest for its impact on the sustainable development and its potential to connect with energy analysis applications. Analysing the energy at the early design stage provides an opportunity to make cost-effective decisions that influence the building life cycle and meet the energy efficiency targets.

The building system analysis involves many functional aspects of a building such as structural integrity, ventilation, temperature control, circulation, lighting, energy distribution and consumption (Azhar et al, 2010). Hence, an ideal opportunity exists for the sustainability measures and performance analysis to be integrated within the BIM model (Azhar and Brown, 2009). BIM includes associated benefits of visualization, built-in intelligent objects of a building model such as spatial data (3D), unstructured data (text), and structured data such as spreadsheets and databases. BIM models not only provide data pertaining to the building geometry but they allow the calculation of volumes and related energy based on the characteristics and orientation of a building.

The Green Building XML schema — known as “gbXML” — was developed to facilitate the transferring process of the information stored in building information models to enable the integration and interoperability between the design models and other engineering analysis tools (Kumar, 2008). Furthermore, gbXML facilitates the exchange of the building information (which includes product characteristics and equipment performance data) between the manufacturer’s database, the BIM models and the energy simulation engines. One of gbXML’s benefits is its ability to carry detailed descriptions of a single building or a set of buildings that can be imported and used by energy analysis and simulation tools. The IFC specification is developed and maintained by buildingSMART International as its “Data standard.” It is registered with ISO as ISO16739 as an open international standard for BIM data that is exchanged and shared among software applications used by the various participants in a building construction or facility management project. It has an open data exchange format that is usually used by model-based applications to exchange data between one another. IFC permits information (i.e., design, analysis, specification, fabrication, construction and occupancy) to be shared and maintained throughout the life cycle of construction projects (Khemlani, 2004). The IFC model consists of tangible components such as walls, doors, beams, and furniture as well as the more abstract concepts of space, geometry, materials, finishes, and activities (Kumar, 2008).

When creating sustainable design, designers are concerned about their ability to evaluate the environmental impact (EI) of the selected materials and components by using available methods and tools. In this perspective, the idea of LCA has emerged as the collection and evaluation of the inputs, outputs and the embodied energy of a product throughout its life cycle (Guinée et al, 2011). While LCA can be used to assess the sustainability of the built environment, its technique provides comprehensive coverage of the product's energy consumption. Thus, its application at the conceptual design stage of building projects will be very useful for designers. In order to analyze the embodied energy of buildings' components, a methodology that integrates BIM models with LCA systems is needed due to its potential to streamline LCA processes and facilitate the rigorous management of the environmental footprint of constructed facilities. Jrade and Jalaei (2013) describe a methodology emphasizing the integration of BIM, Management Information Systems, and LCA that can be used to implement sustainable design for proposed buildings at their conceptual stage all the while taking into consideration their Environmental Impacts. Häkkinen and Kiviniemi (2008) identify the following solutions to integrate BIM tools with LCA systems: 1) linking separate software tools via file exchange, 2) adding functionality to existing BIM software and 3) using parametric formats such as Geometric Description Language (GDL).

Generally, data such as transport, energy, recycling, and case studies are available from various industries. This type of information is useful but finding relevant ones for a specific usage can be extremely difficult. Commercial databases are often inherited in commercial applications or tools. These databases hold data about some specific products that are better than the ones in the free databases. Lehtinen et al (2011) listed a couple of free LCA databases such as CCaLC database in the UK and the US Life Cycle Inventory Database, which is supplied by Athena Sustainable Materials Institute. Athena Impact Estimator allows users to input the building's estimated annual operating energy by fuel type and they can subsequently compare and contrast the life cycle operating and embodied energy and other environmental effects of the building design. It provides a cradle-to-grave life cycle inventory profile for a whole building (Athena, 2012). In LCA terminology, the effects associated with the making, transporting, using, and disposing of products are referred to as “embodied effects.” Until recently, only operating energy was considered, owing to its larger share in the total energy life cycle. However, due to the advent of energy efficient equipment and appliances, as well as more advanced and effective insulation materials, the potential for curbing operating energy has increased and, as a result, the current emphasis has shifted to include embodied energy in the building materials (Crowther, 1999; Nassen et al, 2007). Thus, there is a genuine demand for measures to calibrate the performance of buildings in terms of both embodied and operating energy in order to reduce their energy consumption (Langstone et al, 2008; Treloar et al, 2001).

While green building certification systems can be used as guidance for design, to record performance progress, to compare buildings and to document the outcomes and/or strategies used in the building (Wang et al, 2012), different types of methodology such as Building Research Establishment Environmental Assessment Method (BREEAM) (Baldwin R et al, 1998), Green Star from Australia (GBCA, 2008), and the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) from Japan (CASBEE, 2008) have been developed. More locally, we can also find the Building and Environmental Performance Assessment Criteria (BEPAC) from Canada (Cole et al., 1993) and the Leadership in Energy and Environmental Design (LEED) from the United States (USGBC, 2001). All of these methodologies are widely used to establish the environmental goals’ level of achievement and to guide the planning and design processes. Furthermore, comprehensive tools for environmental assessment can be found (Ding, 2008) such as the whole Building Design Guide (WBDG, 2012) and the World Green Building Council (WGBC, 2008).

Although these tools have an extended use, the LEED Rating System (LEED-RS) has established a strong credibility among the experts (Pulselli et al, 2007). The LEED-RS was evaluated as to its importance as a measurement tool for the environmental performance of a building by 7,500 companies and organization members around the world. Yet, in order to automate the evaluation of the environmental specifications of the proposed building model in BIM at the conceptual design stage, designers can use a sustainability evaluator tool (i.e. EcoScorecard©), which is a plug-in to the BIM tool. This plug-in has the ability to evaluate and document the environmental data for various rating systems such as those of the US Green Building Council “USGBC,” the

Canadian Green Building Council "CaGBC," the Collaborative for High Performance Schools (CHPS) and the National Green Building Standard (NGBS) as well as other third-party product certification systems.

Although the potential of using BIM models for energy simulation is well known, a systematic approach that can be used to share the necessary information is still lacking (Young, et al 2009). The data related to the buildings' HVAC systems and to the internal loads such as occupancy and lighting should be included in the data exchanging process between BIM tools and energy simulation software in order to avoid any repetitive data inputs (Pimplikar and Esmaeili, 2012). The first step to pursue the integration procedure is to test the data inputs and outputs using different interoperable formats and to select the more efficient one. Since the automation process will take place at the conceptual stage of a project's life while doing sustainable design, another aspect of this study is to use an application to evaluate the created model in order to get details about its environmental and sustainability specifications in a systematic way. In this case, users can add up the potential points that can be earned during the design based on the selected green building certification system. This would provide the design team with the opportunity to compare different energy results for the whole model and to analyse the embodied energy of every component in that model. Autodesk Revit®, which is used as BIM tool in this research, provides the opportunity to develop API's that can be used to create custom tools that plug directly into Autodesk Revit®. This would extend the functionality of the BIM tool and would allow users make well-informed decisions in selecting optimum sustainable building components.

5.3. SCOPE AND SIGNIFICANCE OF THE STUDY

This paper proposes a methodology that can be used to implement an integrated platform to do sustainable design for new buildings at their conceptual stage and afterwards analyze and simulate their energy and day lighting respectively and assess their sustainability. The methodology is implemented by designing and developing a model that simplifies the process of designing sustainable buildings and transmitting the design information to energy analysis tools to implement energy and lighting analysis as well as identifying and listing the potential certification points that can be earned based on the selected system for sustainability. The methodology incorporates an integrated model capable of guiding users when performing sustainable design for new building projects. It incorporates the following five modules: 1) A Database Management System (DBMS) module, 2) An Energy and lighting analysis module, 3) A Life Cycle Assessment (LCA) module, 4) A LEED accreditation module and 5) A cost estimating module. Each of these modules is linked to one or more databases containing necessary data and information. The major task of the model is to collect lists of green products and certified materials and have them linked to the building database in the BIM tool. Creating and linking such a database to the BIM tool helps users design and animate sustainable buildings in the BIM environment easily and efficiently at the conceptual stage. Part of this integrated methodology is to develop new plug-ins and customize the existing ones built into the BIM tool in order to assist users to connect their design module with the abovementioned five modules in an efficient and consistent manner. The main objectives of this study are:

• Investigate the feasibility of creating full integration between BIM, Energy and lighting analysis tools,

• Collect, create and store series of design families that incorporate sustainably certified components in a database in an attempt to improve the workability and capability of the BIM tool used to do sustainable design at the conceptual stage.

• Create and develop an efficient framework for this integration that takes into consideration the sustainable design requirements and the functionality of the BIM tool,

• Develop a BIM sustainable design model that incorporates the five previously mentioned modules,

• Analyze the data and information associated with the proposed building's model, which is transmitted during the transformation process from one file format to another to identify how much of this data was retained and how much was lost.

Numerous types of software used in the construction industry, such as Autodesk Revit Architecture©, Autodesk Ecotect, Integrated Environmental Solutions (IES-VE), Microsoft Excel© and Athena® Impact Estimator© were used in the development of the integrated model. The successful implementation of such a model represents a significant advancement in the ability to attain sustainable design of a building during the early stages of its life, to evaluate its EI and to list its potentially earned certification points and the associated costs.

5.4. METHODOLOGY AND DEVELOPMENT

The major objective is to develop an automated methodology that helps a designer do 3D conceptual design of a sustainable building and to analyze and simulate its energy as a whole and for every one of its components. Since the proposed methodology integrates different applications, it will be implemented through six sequential phases. Fig. 5.1 illustrates the sequential flow of implementing the integrated methodology.

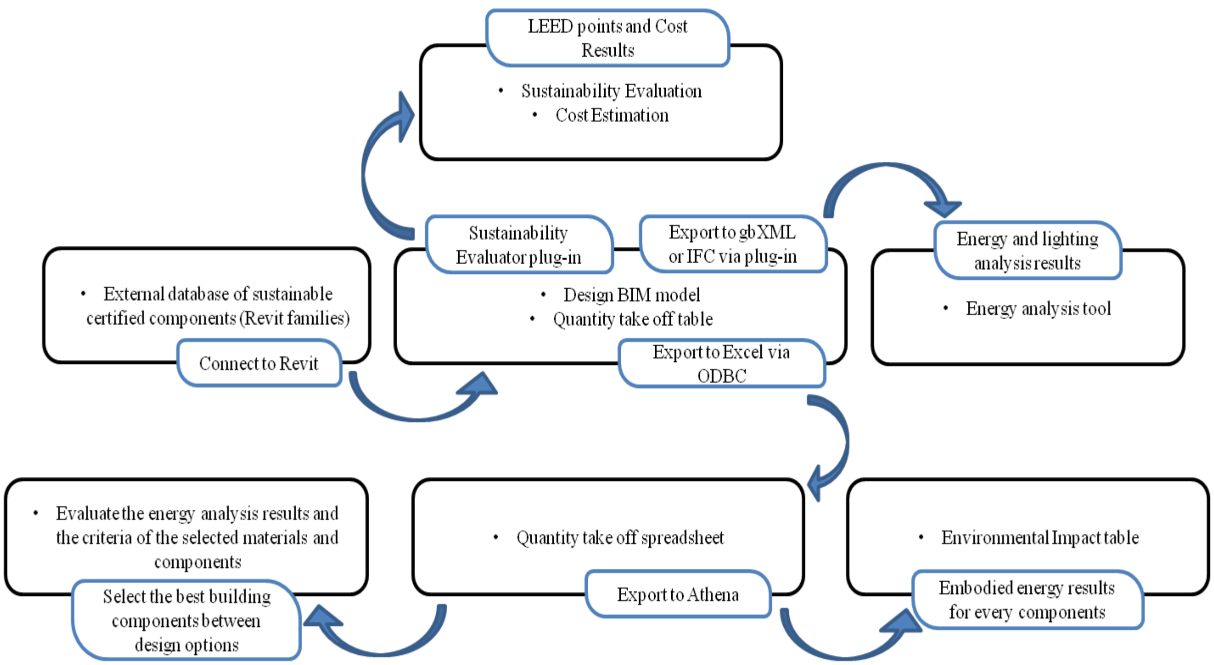

Figure 5. 1. Sequential flow of implementing the integrated methodology

Phase 1 consists of designing the model's relational database needed to design sustainable building. Loucopoulos (1992) states that a consistent information system depends on the integration between databases, programming languages, and software engineering and that its lifecycle incorporates the interrelated technologies of conceptual modeling and database design. The design and development of this database is accomplished in two steps starting with the conceptual modelling and ending with the physical implementation. First, the problem investigation and user needs are recognized based on a comprehensive literature review. Then the database requirements are identified and the conceptual design is carried out. Secondly, the implementation of the data model requires that the transformation process be made from the conceptual to the logical design (Jrade and Alkass, 2007). Only afterwards is the physical implementation made by creating a list of related tables used to store the collected data based on the selected Work Breakdown Structure (WBS). The information related to the green materials is stored in an external database in the form of predefined design families that can be recognized by the BIM tool. The reason for developing a separate database is to have it loaded every time the BIM tool (Revit) opens and this is done by defining its path, which is linked to the predefined library of Revit. The data related to the green materials is saved as family files (RFA) or Revit files (RVT), which can be identified by the BIM tool. Thus, in the external sustainable database, up to 3,000 design families are collected from the literature, suppliers' web pages, USGBC and CaGBC websites as well as published data and are arranged based on the 16 divisions of the Masterformat WBS. Different types of information such as details about the materials used, suppliers' contact data, assigned keynotes, potential LEED points and assembly codes are stored in the external database.

Phase 2 focuses on customizing the BIM tool to fit the modularity requirements of the model. The first step is to design and implement a 3D module capable of storing newly created families, in the BIM tool, and their associated keynotes for components commonly used in residential buildings by using certified green materials. The module is linked to the database developed in Phase 1. Keynotes are textual annotations that relate text strings to specific elements in the model, which are in turn linked to an external text file. It can be used as an external link to the element itself with a specific style and specifications so it can be used as a Revit family. This means that a user can insert different text family types in Revit. Keynotes can be assigned to elements which are typically used if the user wants to note an entire assembly, such as a wall assembly. A material type keynote is used to note a specific material in Revit (i.e. concrete, gypsum board or acoustical tile). The sixteen Masterformat divisions present the main WBS applied in this research. It is very important to select a unique code for each item that is presented in a separate line in the database to ease and simplify their usage. The coding system allows users to accelerate the process of retrieving any necessary information from keynotes. There are five-digit numbers that represent the divisions, subdivisions, elements and material names. Creating the families is based on modifying the inherited resources by adding new parameters. Customizing and duplicating an existing family adds an important feature to the model. For instance, the families built into the BIM tool consist of different types such as walls, floors, stairs, windows, and doors.

Phase 3 concentrates on developing a plug-in, which is a type of algorithm that adds functionality to the BIM tool by integrating it with the energy analysis and simulation tools. The C# programming language is used in developing the plug-ins that will be applied to the BIM tool. In this algorithm, the exporting process of the materials quantity take-offs into gbXML and IFC is done automatically and saved in a pre-defined location by the plug-in. Then the plug-in recalls ECOTECT.exe to pop-up and opens the saved files from that pre-defined location. To load and run the plug-in, an add-in which includes information used by the BIM tool must be added. It is a file located in a specific location that BIM tool looks at while it is loading. Therefore, the whole process of transferring data from BIM to the energy analysis tool is done automatically by using the plug-in.

Phase 4 consists of designing energy analysis and simulation modules that help to export the design created in the BIM tool in the IFC and gbXML file formats. One of the energy analysis tools used in this research is Ecotect, due to its efficiency in evaluating the thermal and solar gains for the architectural designs of proposed buildings. It easily creates or cleans up models in a format that includes both the geometry and the zones of a building, besides having interoperability potentials with other tools. This interoperability makes it an ideal tool to import and export the design between BIM tools, which generate the geometry of the proposed building, and different energy analysis tools. IES-VE, which can be linked to the BIM tool as a plug-in, provides information for thermal analysis, value engineering, cost planning, life-cycle analysis, airflow analysis, lighting, and occupant safety all in one unified system (Khemlani, 2006). IES-VE contains an Integrated Data Model that captures all the information related to the proposed building including the geometric data, which is needed to do all the necessary analyses. Yet, it must be said that the 3D geometric information can also be imported straight from the BIM tool using the gbXML file format. Construction materials can also be selected from the IES-VE built-in database, which is known as the Apache construction database.

Phase 5 consists of designing an LCA module that interconnects the design created in the BIM tool with the LCA tool through an ODBC connection to directly transfer the materials' bill of quantity into the latter tool in order to evaluate the environmental impacts of these materials.

That LCA module is connected to an external database that stores the extracted quantities of materials, which is then imported into the ATHENA Impact Estimator© via a text file exchange format. The authors elected to use ATHENA Impact Estimator© for Buildings because it is commonly used by the North American construction industry and because it is designed to evaluate the whole building and its assemblies based on the internationally recognized life cycle assessment (LCA) methodology. When using this tool, the focus is on analyzing the embodied energy of the architectural and structural systems that are used in the 3D conceptual design.

One of contributions of this research is the ability to measure the transport energy, which is one significant component of the embodied energy used to transfer materials and building components from suppliers' locations to the building site. The IE tool does not recognize this type of energy and accordingly it does not have the capability to calculate it. Transport energy is a function of the weight of materials, the transport method and the travelled distance. From these three factors a reasonably accurate calculation of the transport embodied energy can be done. Many materials are delivered to the site by rigid trucks, thus the developed model considers this as one of the inputs stored in the database developed in phase 1.

Phase 6 includes the design and development of a green building certification and cost estimating module, which is linked to the BIM and Energy analysis modules. This module contains data collected from the suppliers' and publishers' webpages, which are retrieved from the created model by using the sustainability evaluator plug-in that is loaded into the BIM tool. The authors collected information about sustainable materials and components from the manufacturers' and vendors' websites and from using the smart BIM green components, which can be detected by the sustainability evaluator. In the sustainability evaluation results, there is detailed information about every component, which includes the potential LEED points that can be gained if these materials or components are used in the design. This information is stored in the external database of the BIM tool. Therefore, when designers model the design for a proposed building project in 3D and select any of these sustainable materials or components, the potential LEED points gained by these selected items are identified and stored in the schedule associated with the BIM model. Afterwards, users will add up these LEED points to identify the potential number that the proposed building can earn and accordingly its potential level of certification (Certified, Silver, Gold, or Platinum). Furthermore, the associated cost will be generated by linking the model created in the BIM tool with the cost module, which is linked to the database that stores information about green and certified materials. The associated cost of the developed design is then calculated based on R.S. Means published data.

The development of the model described in this paper focuses on automating the process of connecting the output of the BIM module with other different modules, (energy analysis and day lighting simulation, embodied energy of the building's components and Green Certification System and associated costs). The model is an integrated tool that helps owners and designers share a variety of information at the conceptual design stage of sustainable buildings. It assists designers in comparing and evaluating each design family and its associated components that are selected during the conceptual design taking into consideration the materials' selection criteria.

Fig. 5.2 shows a flowchart of the integration process that is used in this study. It determines the processes applied to the design created in the BIM tool while considering all related criteria and specifications based on the described phases. Fig.5.3 illustrates the model's architecture when the input section includes the certified components stored in the database, based on the Masterformat WBS, containing keynotes and families as well as suppliers' information. Project orientation and the specified green building rating system for sustainability analysis are identified as inputs. The criteria section includes the green building rating system as well as the environmental performance and principles to select green materials. The main output will be a sustainable design in 3D mode of the proposed building that includes lists of the selected sustainable materials and their environmental impacts as well as the results of the energy simulation and daylight data analysis. The innovation highlighted in this paper describes the model's different modules, which are integrated with each other through an automated process that uses newly created plug-ins as well as the existing ones after improving their functionality in an attempt to assist users start the design of a proposed sustainable building at the conceptual stage of its life.

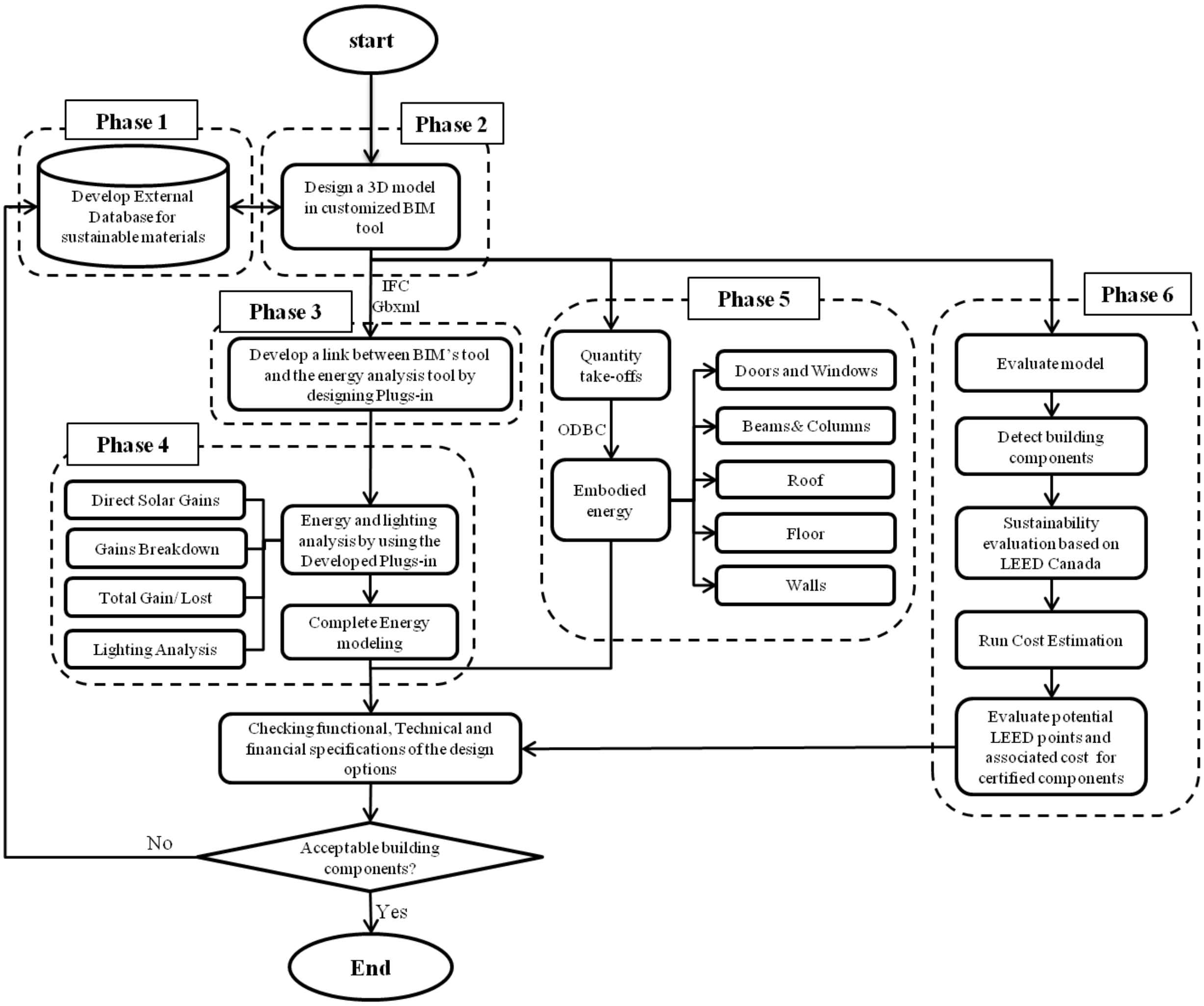

Figure 5. 2. Flowchart of the integration process

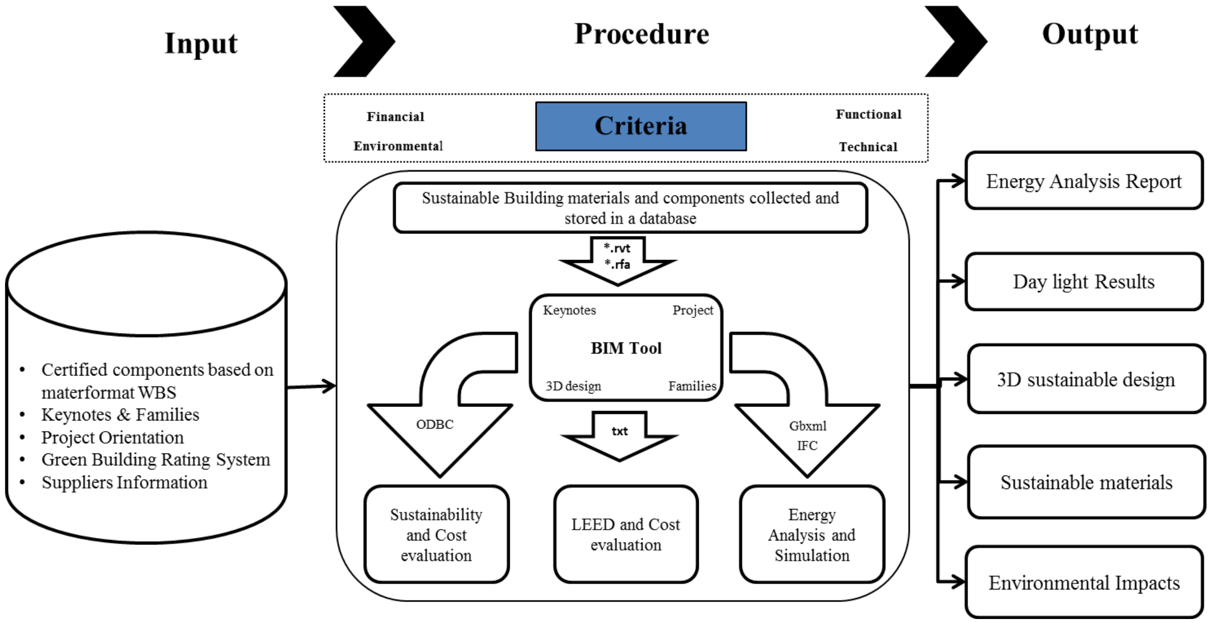

Figure 5. 3. Model's Architecture

This platform provides a suitable environment to establish a Decision Support System (DSS) to help the design team decide on the selection of the best type of sustainable building components and families for proposed projects based on defined criteria (i.e. Energy consumption, Environmental impacts and Economic properties) in an attempt to identify the influence of the design variations on the sustainable performance of the whole building. The final design will be influenced by the results of the energy and lighting analysis, the LCA and Environmental Impact and embodied energy results, and the sustainability evaluation of every building component based on the LEED rating system, as well as the initial costs of these components. These results represent a reasonable perspective to evaluate how far the design deviates from the standards and from the owners' expectations.

5.5. TESTING AND VALIDATION

This section tests and validates the capabilities of the developed model. Its performance is examined through the use of an actual eight-floor residential apartment building project that is currently under design in the city of Ottawa. The proposed construction site has a total area of 10,665 ft2, the building's gross area is 40,810 ft2 and it has a perimeter of 332 ft. The total number of units in the proposed building is fifteen where the first seven floors have two units each while the eighth one consists of one unit with a gross floor area of 5,130 ft2. The authors created a conceptual design of the current project where its associated sustainable components and materials were selected from the developed database. The components used in creating the design of the case building had their specifications very close to the ones used in the real design. Every component, such as the floor, walls, roof, and windows has its associated LEED information linked to the families inherited in the BIM tool and are already defined in the database of the sustainability evaluator tool (Ecoscorecard), which includes the manufacturers' web pages and contact information. The developed model will be used to analyse and simulate the energy and lighting of the project's 3D design and to evaluate its sustainability by calculating the accumulated LEED points that can potentially be earned during the conceptual design stage. This process is implemented in four steps, wherein the model's capabilities and performance are measured using the inherited modules.

5.5.1. 3D Sustainable Design (Step1)

The BIM tool (Autodesk Revit Architecture©) is applied to do the sustainable conceptual design of the case building by using green families and their related keynotes stored in the external database. Once these families' keynote file is linked to the building model, users will select the most appropriate type of certified materials and components for their design. As explained in phase 1, the external database contains detailed information about the suppliers of the green materials used in every family. More than 80% of the components and families used in the case building had their LEED certification points supplied by their manufacturers and stored in the developed external database.

5.5.2. Energy Analysis and Lighting Simulation (Step2)

In order to have an accurate energy analysis of the case building, its created 3D geometric model must be converted into an analytical model. First, we have to convert all the spaces into rooms. In the BIM tool, rooms are considered to be the equivalent of zones that need to be defined. A thermal zone is a completely enclosed space bounded by its floors, walls and roof and is the basic unit for which the heat loads are calculated. The extent of a "room" is defined by its bounding elements such as walls, floors and roofs. Once a "room" is defined for the purpose of analysing the building's energy, these bounding elements are converted to 2D surfaces representing their actual geometry. However, overhangs and balconies, which do not have a room, are considered as shading surfaces. In order to determine whether a room is an interior or an exterior one it is important to define its adjacent in the analytical model. By using the developed plug-in that is loaded in the BIM tool, designers will directly transfer the created model of the building to the energy simulation and analysis tool (Ecotect©) using both the gbXML and IFC formats as shown in Fig. 5.4. Moreover, by using the IES-VE plug-ins, which is added to the BIM tool, transferring the BIM model into IES-VE is possible using the gbXML format.

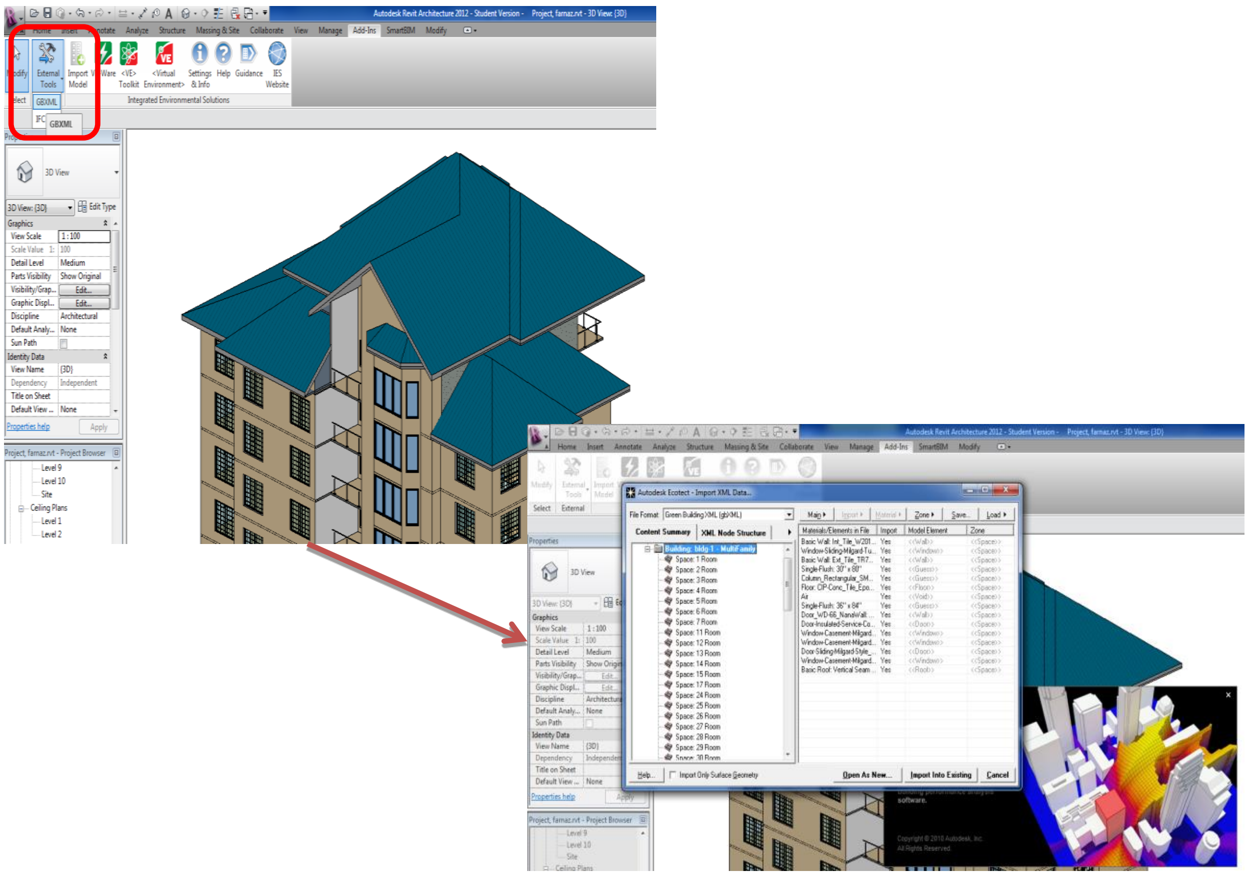

Figure 5. 4. Snapshot of transferring BIM model directly to Ecotect via the developed Plug-in based on gbXML file format (Same process for IFC format)

In order to test what type of data was included in each of those file formats, a careful comparison will be necessary. The created case building model is tested for building materials, thickness, geometry (area and volume), building services, location, and building type. All the input variables are kept constant in the base case while the testing is done with one alteration at a time.

Fig. 5.5 shows how wall coordination data is represented in gbXML and IFC by elaborating on the relational and organized data representation in each format. The IFC schema represents the coordinates and dimensions of an IfcWall object. IfcWall is a subtype of IfcBuildingElement. IfcBuildingElement is a subtype of IfcElement, which generalize all the elements that make up a specific component such as walls, windows, or doors.

IfcPlacement has three subtypes: IfcAxis1Placement defines the direction and location in three dimensional space of a single axis. IfcAxis2Placement2D is used to locate and originate an object in two dimensional spaces and to define a placement coordinate system. IfcAxis2Placement3D is used to locate and originate an object in three dimensional spaces and to define a placement coordinate system. A wall gains its geometric position and orientation by virtue of a reference to axis2_placement (IfcAxis2Placement) that in turn references a Cartesian point (IfcCartesianPoint), several directions (IfcDirection) and its starting point (IfcVirtualGridIntersection). IfcCartesianPoint has an attribute called Coordinates, which is a list of 1 to 3 IfcLengthMeasure objects. This is where the coordinates are represented.

In order to compare the IFC approach and the gbXML approach, the same examples are used and evaluated. As mentioned earlier, gbXML is developed based on XML, which captures data information representation but not the relationships among them. Fig. 5.5 shows a representation of the gbXML geometry information schema. All the geometry information imported from the BIM tool is represented by the “Campus” element. The global child element “Surface” represents all the surfaces in the geometry. There are several attributes defined in a “Surface” such as “id” and “surfaceType.” Every “Surface” element has two representations of geometry, “PlanarGeometry” and “RectangularGeometry.” They both carry the same geometry information. The purpose of this is to double-check whether the translation of geometry from the BIM tool is correct or not. Every “RectangularGeometry” has four “CartesianPoint” elements, which represent a surface. Every “CartesianPoint” is represented by a three dimensional coordinate (x,y,z).

There are only five levels to transverse and to get all the coordinates of an “Exterior Wall” location. It is also easy to add other surfaces according to the schema defined in Fig. 5.5. In addition, every polyloop, which contains a list of coordinates that makes up a polygon in three-dimensional space, follows a right-hand rule defining the outward normal of a surface.

IFC adopts a comprehensive and generic approach to represent an entire building project. IFC representation was also extended in the building commission domain and implemented in several case studies (Akin, 2004).

However, as it is shown in Fig. 5.5, gbXML has the ability to carry building environmental sensing information. In terms of geometry, the generic approach of IFC has the ability to represent any shape of the building geometry, while gbXML only accepts a rectangular shape, which is an inherent limitation of the BIM tool in exporting and the energy simulation tool in importing the design information. Furthermore, IFC uses a “top-down” and relational approach, which yields a relative complex data representation schema and a large data file size while gbXML adopts a “bottom-up” approach, which is flexible, open source, and a relatively straightforward data schema. The “top-down” approach can trace back all the semantic changes when one value of the element in the schema changes. However, it is very complex to be programmed and to be implemented in a software application. The “bottom-up” approach has fewer layers of complexity.

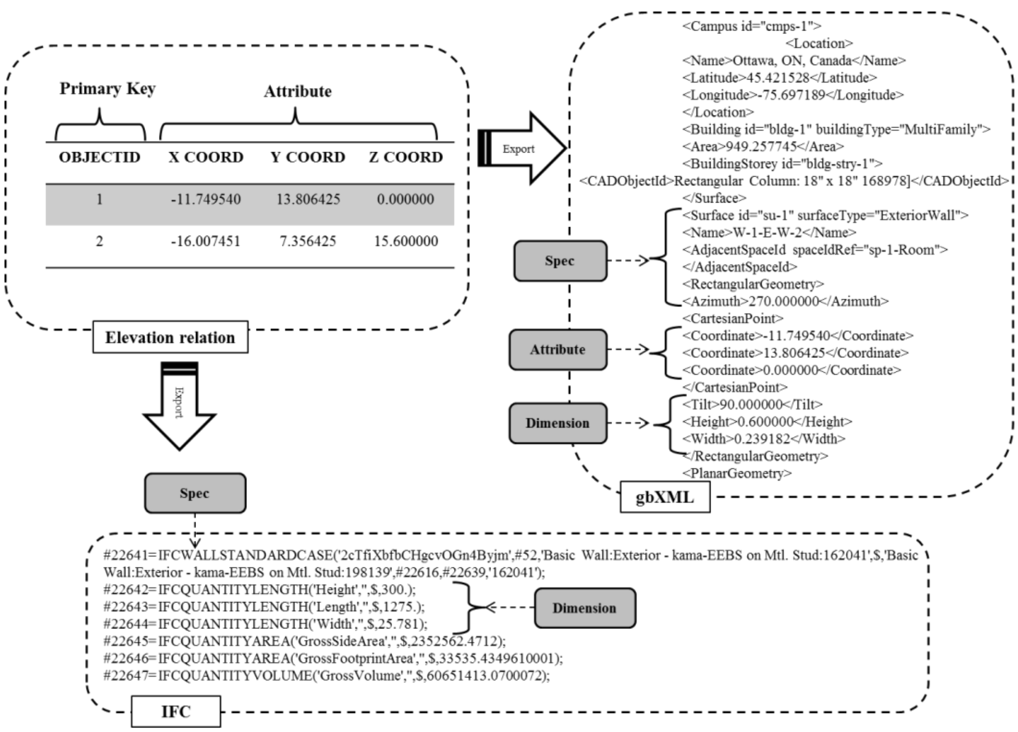

Figure 5. 5. Example of wall information exchanged through gbXML and IFC file formats

Table 5.1 shows the result of comparing the information transferred via gbXML and IFC files from the BIM tool. Table 6.1 shows that the IFC file contains geometric information such as shapes, areas and volumes but is not populated with other critical information such as location, construction assignments and units. Since the IFC file does not contain all the necessary information, assumptions for lighting, equipment and people loads as well as its air flow data is going to be inferred differently from the data translated into other file formats. However, this is not a limitation of IFC, but is related to the way the design of the case project is modeled in the BIM tool and to what extent that tool supports the IFC standard. The gbXML file, similar to the IFC, contains geometric information such as shape, areas and volumes. However, it is further populated with information about location, and construction assignments. Referring to Table 5.1, it can be seen that the gbXML file is also able to transfer other information such as building type (residential building) and building services (VAV single duct). Thus, in order to validate the information that is not transmitted, the gbXML file is modified so that it can recognise the information related to the location, building services and construction assignments while executing the transferring process.

The authors realized that missing a single piece of information during the transfer process would have a big influence on the end results. For instance, in this specific case example, the IFC file does not contain the information related to the project location as defined in the created model; hence, when imported into the energy simulation tool (Ecotect), the model would assume the default values for the location given when creating the digital model in Revit. In order to discern that the information related to the selected material used in the model has been completely transmitted over to the energy simulation and analysis tools, a new material is assigned to the 3D model of the case building. The wall's material is changed to a timber frame wall that consists of brickwork (outer leaf), cavity, plywood (lightweight), mineral fiber slab, and cavity and gypsum plasterboard. However, the option selected in the IES interface for the construction assignments (exterior wall) is kept unchanged.

A quick scan of the IES results shows that the data is kept unaltered. This means that the newly assigned material in the model does not have any type of effect on the results. Table 5.1 also shows that even though a component such as a wall is modeled in the BIM tool with its associated materials, the information transferred to IES is kept unchanged. To clarify this result, in another case, the timber frame wall was modeled as the wall material, and the same option was selected in the IES interface, which is a timber frame wall. The difference in the results indicates that the selection in the Revit-IES interface overrides any selection made when modeling the building in Revit. This is important because it indicates a gap in transferring the information of the building model in Revit and analytical model in IES-VE.

Table 5. 1. Comparing the information transferred from BIM model and imported as gbXML and IFC formats into different energy analysis tools

	BIM Model	**GbXML file imported into Energy Simulation Tool (Ecotect)**	**GbXML file imported into Energy Simulation Tool (IES-VE)**	**IFC file imported into Energy Simulation Tool (Ecotect)**
Units	Feet and inches	Metres	Metres	Meters
Area	5,130 ft^2	5,130 ft^2	5,130 ft^2	476.59 m^2 (equals 5,130 ft^2)
Volume	359,100 ft^3	359,100 ft^3	359,100 ft^3	10,169 m^3(equals 359,115 ft^3)
Building Components	Basic Wall: Int_Tile_W201E_PermaColorTM_Laticrete	Basic Wall: Int_Tile_W201E_PermaColorTM_Laticrete	4” facebrick with 4” light weight concrete block	-
	Floor: CIP-Conc_Tile_Epoxy_F133A_LATAPOXY-2000_Laticrete	Floor: CIP-Conc_Tile_Epoxy_F133A_LATAPOXY-2000_Laticrete	8” light weight concrete floor deck	-
	Basic Roof: Vertical Seam 12" OC - Solid Substrate	Basic Roof: Vertical Seam 12" OC - Solid Substrate	Sloping roof including loft (2002 UK reg.)	-
	Window-Sliding-Milgard-Tuscany_Series-Horizontal	Window-Sliding-Milgard-Tuscany_Series-Horizontal	Large Double Glazed windows (Reflective Coating	-
	Door-Sliding-Milgard-Style_Line-Patio: 60x80	Door-Sliding-Milgard-Style_Line-Patio: 60x80		-
Building Services	VAV Single duct	VAV Single duct	VAV Single duct	VAV Single duct
Building Type	Residential	Residential	Residential	Residential
Place and Location	Ottawa, ON	Ottawa, ON	Ottawa Macdonald-Cartier Int'	Boston, MA

Looking at Table 5.1 it can be concluded that, for that specific case project, the mapping to the gbXML file format is much more complete than IFC because it transfers the building type and location and provides much more detail in the "results" section of Ecotect. Fig. 5.6 shows sample results of the day lighting analysis of the created case project that are generated out of both the Ecotect and IES-VE tools and Fig. 5.7 shows sample of the thermal analysis results generated by these tools. In Fig. 5.6, day lighting simulation provides a visualization measurement based on gbxml and IFC file formats of the day light that is gained by every single surface inside the building model as well as the building's exterior wall surfaces, which is supplied as a percentage of the solar light each surface can get. For instance, for the fourth floor, the maximum percentage of solar gains for corner areas is around 45% while the minimum percentage is 4.8%, which corresponds to the central areas located far from the openings. IES-VE provides a solar analysis with 3D visualization showing the amount of light, which in this case varies between 59.45 kwh/m² and 1,325.41 kwh/m² for the whole building.

In Fig. 5.7, a diagram of total gains is based on the outside temperature ranging from -26 ˚C to 32.5 ˚C for the City of Ottawa for all visible thermal zones. The maximum heat loss for the temperature of -26 ˚C is -166 wh/m² and the maximum gain is 108 wh/m² for 31 ˚C. The part of the diagram with condensed points is for the temperature between 0 ˚C to 20 ˚C, which gives an average of -45 wh/m² loss of energy and 10 wh/m² energy gains respectively. Gains breakdown results show the percentage of the overall gains/losses for all visible thermal zones through different colors for Conduction, Solar-Air, Direct Solar, Ventilation, Internal and Inter-zonal for a whole year from January 1st through December 31st. As illustrated, conduction has a maximum overall loss with 64% (around 900 wh/m²) and direct solar has tremendous gains with 70.2% of energy gains (around 500 wh/m²). IES-VE also gives a total annual energy analysis manifesting the total system energy based on power (kw) for the whole year. It also shows that the maximum energy consumption of the building is between November and April with an average of 450 (kw) for the whole system.

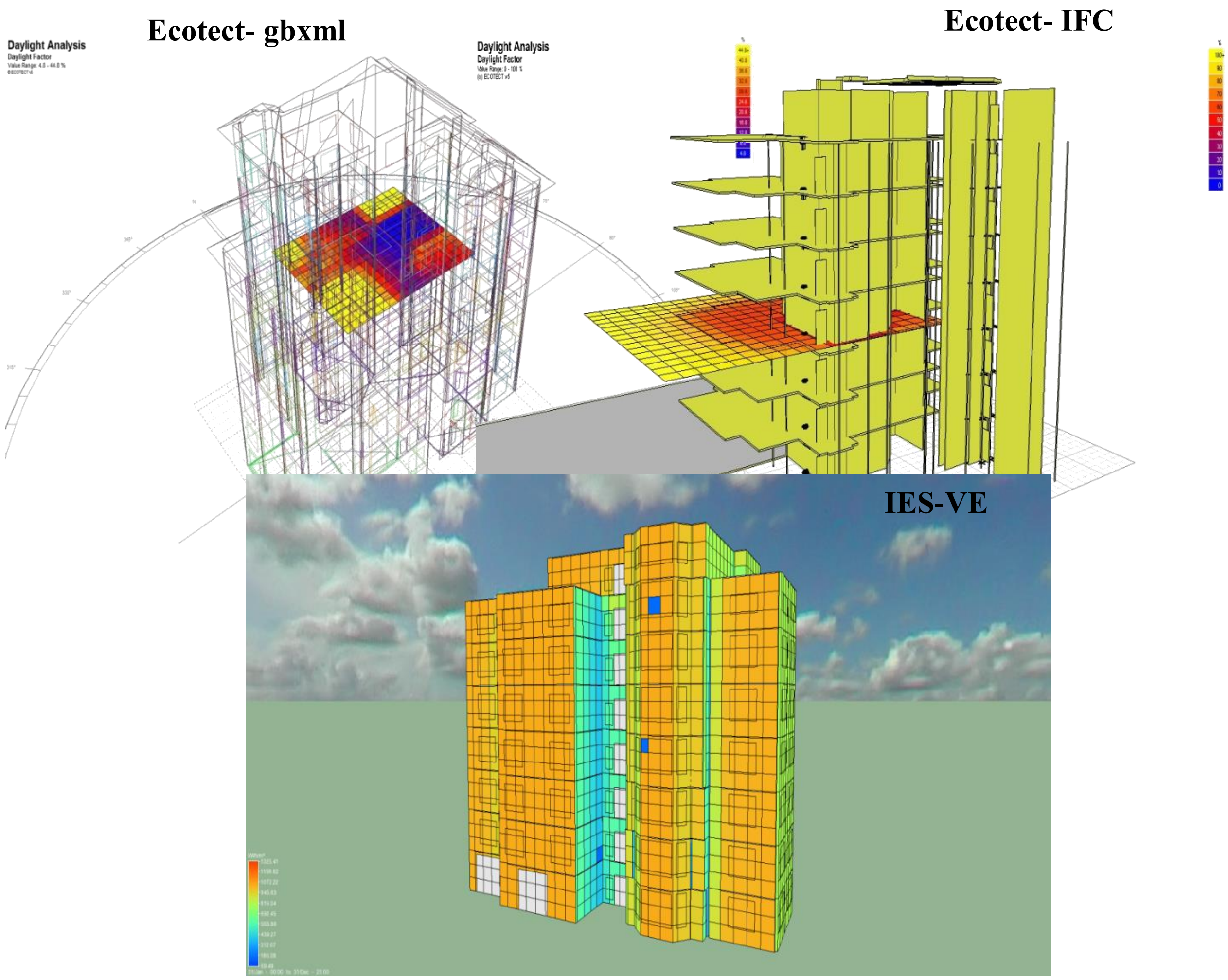

Figure 5. 6. Snapshot of the sample day lighting simulation in Ecotect and IES-VE

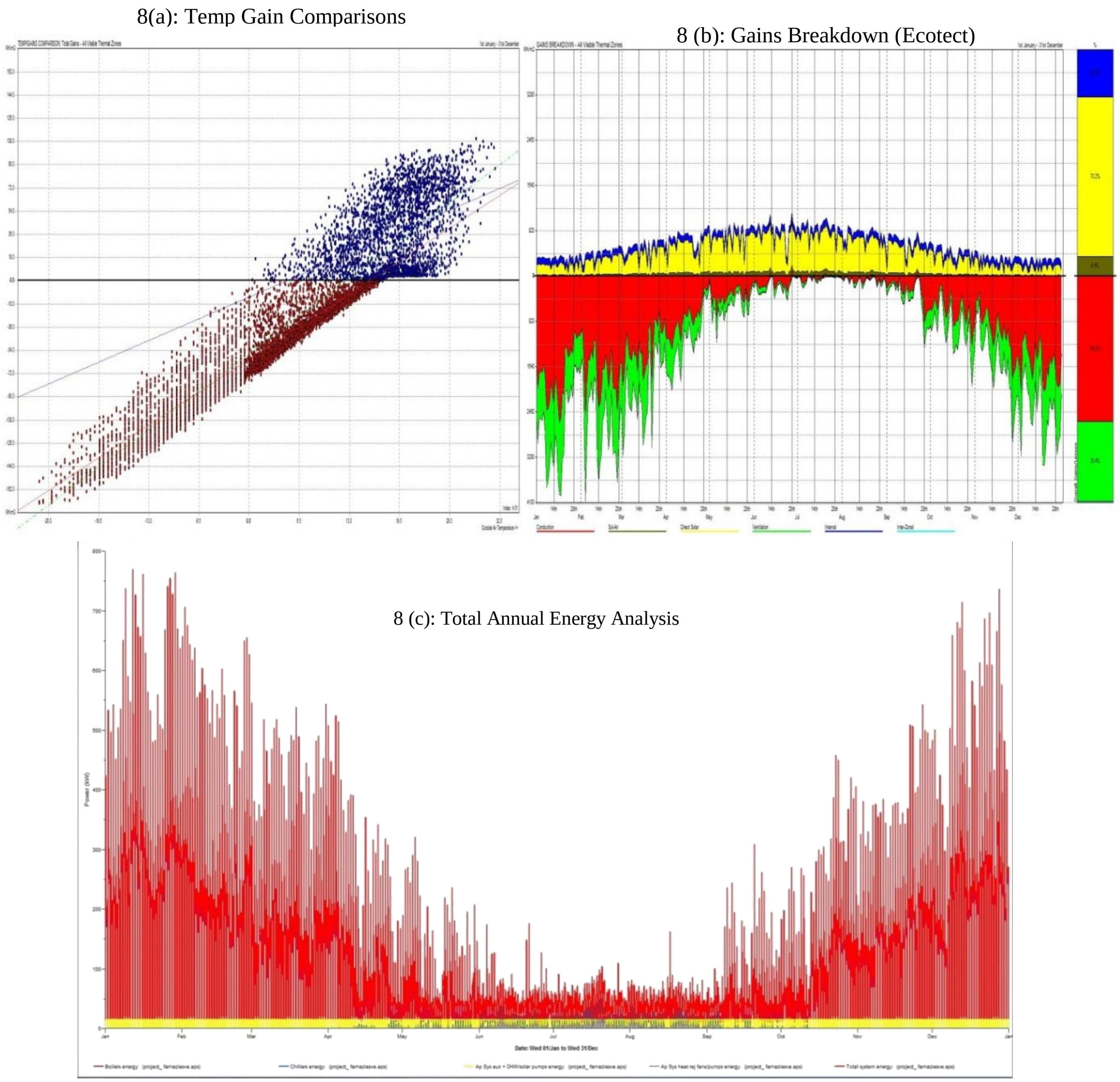

Figure 5. 7. Snapshot of the sample thermal energy analysis in Ecotect and IES-VE

5.5.3. Embodied Energy Analysis of the Building Components (Step 3)

Once the conceptual design is finished and the energy is analyzed, the building is assessed and analyzed based on the sustainability requirements using the LCA module and its associated tool (ATHENA® Impact Estimator©). Using the Impact Estimator (IE), users can calculate the primary operating energy including the embodied energy (the energy used to extract, refine and deliver energy) and the related emissions to air, water and land over the life cycle of the case building. Furthermore, users can compare the life cycle of the operating and embodied energy and other environmental effects of the design created for the case building and they will better understand the inherent trade-offs associated with the increase of the envelope materials (e.g., insulation), which can reduce the operating energy consumption.

Transportation embodied energy is dependent on the type and number of trucks, the travel distance between suppliers and construction site, and material properties (i.e. size and weight). In order to demonstrate the model's capabilities, four different types of trucks (as listed in Table. 5.2) are taken into account when identifying the required number of trucks. In this study, a gross vehicle weight (GVW) is considered as the maximum weight value of a vehicle that includes weight of a vehicle and cargo and a payload is defined as the total weight of all cargo that a vehicle carries. Also, the size of the load in the truck bucket is limited to 53×13.5×8.5 ft (L×H×W) (Irizarry et al, 2013). Using the properties identified above and quantity of material for a given order, the required number of trucks can be determined as it is shown in the algorithm flowchart represented in Fig. 5.8. The proposed algorithm selects a combination of trucks based on the minimum value of fuel consumption. Then, the fuel consumption value is calculated according to the distance traveled per unit of fuel used in miles per gallon (MPG). The distance measurement can be done by using the geospatial method used by the BIM tool that specifies the geographic location for the project. It uses an Internet mapping service to visualize the project location by searching its street address, or the longitude and latitude of the project.

Table 5. 2. Descriptive attributes for each type of trucks selected for the case building

Truck Type	**GVW (lb)**	**Payload (lb)**	**Fuel Consumption (MPG)**	**MPG for empty truck**
1	36,300	25,300	-0.0246W+6.63	6.62
2	60,600	40,800	-0.0258W+6.285	6.26
3	80,000	55,750	-0.0255W+6.205	6.18
4	92,000	66,200	-0.0263W+5.885	5.86

W=Total Weight of Load (1000xlb).

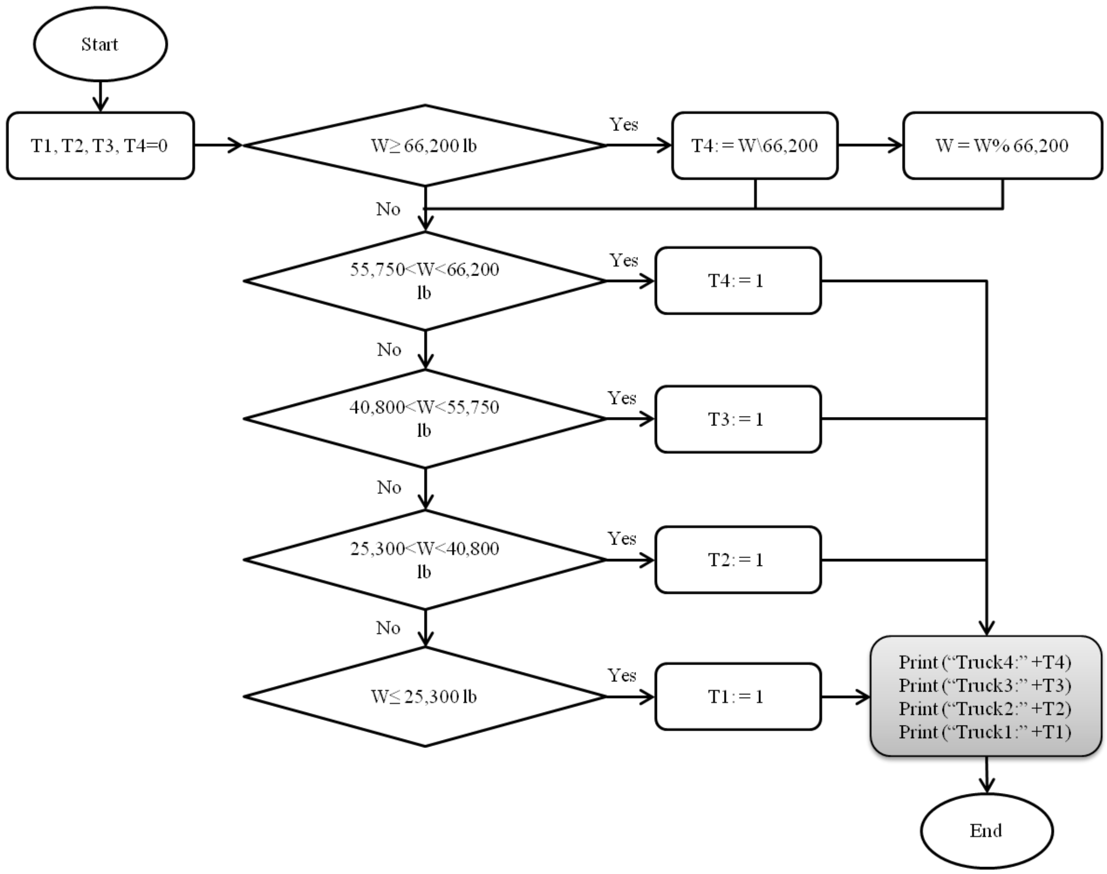

Figure 5. 8. Algorithm's flowchart to select the number of trucks based on the weight of building materials and components

First, we input the necessary information such as geographic location, building life and occupancy/type and, if desired, annual operating energy values into the ATHENA IE. Second, the exported bill of quantities extracted in Step 1 is imported as a text exchange file format into ATHENA® Impact Estimator©. Pre-set dialogue boxes prompt users to describe the different assemblies, such as entering the width, span and live load of a floor assembly. The embodied energy of every building component is calculated and its result is generated and supplied as shown in Fig. 5.9. IE takes into account the energy used to construct the structural elements of the building, the emissions to air, water and land associated with the on-site construction activity as well as the energy used to transport the materials and components from the manufacturer to a national distribution centre and from that centre to the building construction site. As illustrated in Fig. 5.9, in the case building, it is obvious that the wall materials have the highest embodied energy consumption with a total of 15,456,764 MJ based on different types of energy description. Beams and columns have the second highest embodied energy consumption

(8,355,880 MJ), especially in the case of natural gas. Furthermore, 22,112,368.4 MJ of the energy consumed in this building is operating fossil fuel energy while 23,736,933.5 MJ is embodied fossil fuel energy.

To calculate the transport energy, the algorithm receives the weight of every building component (lb) and implements the truck selection procedure. Then, the distance calculator which is integrated into Revit uses the API of Google Maps to calculate the distance between the location (origin) of the materials' suppliers and the location of the project site (destination) once the required postal codes are entered by the user. When all the required data (i.e. weight of the material, postal codes of origin and destination) is entered, the algorithm calculates the transportation energy of every building component (MJ) as well as the number of trucks and their types. For example, by considering the walls' materials in the case building and by assuming a unit weight of 55 lb. /SF and a calculated total surface area of 16,250 SF for all the walls, the total weight of the wall material will be around 893,750 lb. Using the developed algorithm shows that a combination of one truck of type 2 and thirteen trucks of type 4 is a proper option for transporting the materials. While the fuel consumption for truck 4 and truck 2 are 4.14 MPG and 5.43 MPG respectively, entering the postal code of the origin and destination would lead to an approximate measurement of the distance to be 422 miles, thus the consumed embodied energy for transporting the wall's material is calculated to be around 1,402.83 G (184,836.88 MJ). The same processes are applied for the rest of the building components and accordingly the total transportation energy for that case building would be calculated to be around 15,641,600.88 MJ.

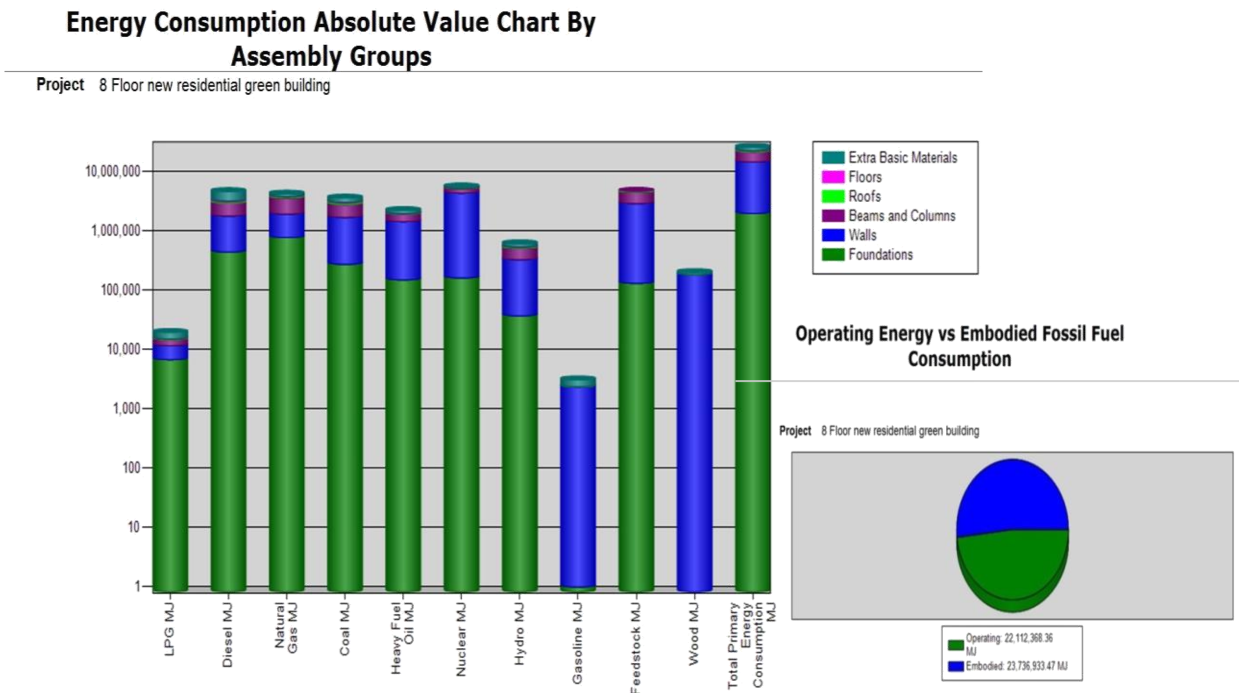

Figure 5. 9. Embodied Energy analysis of each building component in the designed model

5.5.4. Environmental Evaluation and Calculation of the Potential LEED Points (Step 4)

By running the sustainability evaluator plug-in (EcoScorecard) loaded into BIM tool, one can evaluate the created case building model based on different green building rating systems as previously described. The result of the EcoScorecard is shown in Fig. 5.10, where 54.2% of the cases building model's components are compiled from sustainable materials and families that are already defined in the Smart BIM database and detected by the EcoScorecard. By selecting the desired green building rating system and clicking the "evaluate" button, we are able to see the analysis results in detail and save them as a PDF file. LEED® Canada New Construction v1.0 is used to evaluate the designed model for the case building. Thereafter, users are able to identify the potential points earned by the design based on the information provided by the EcoScorecard.

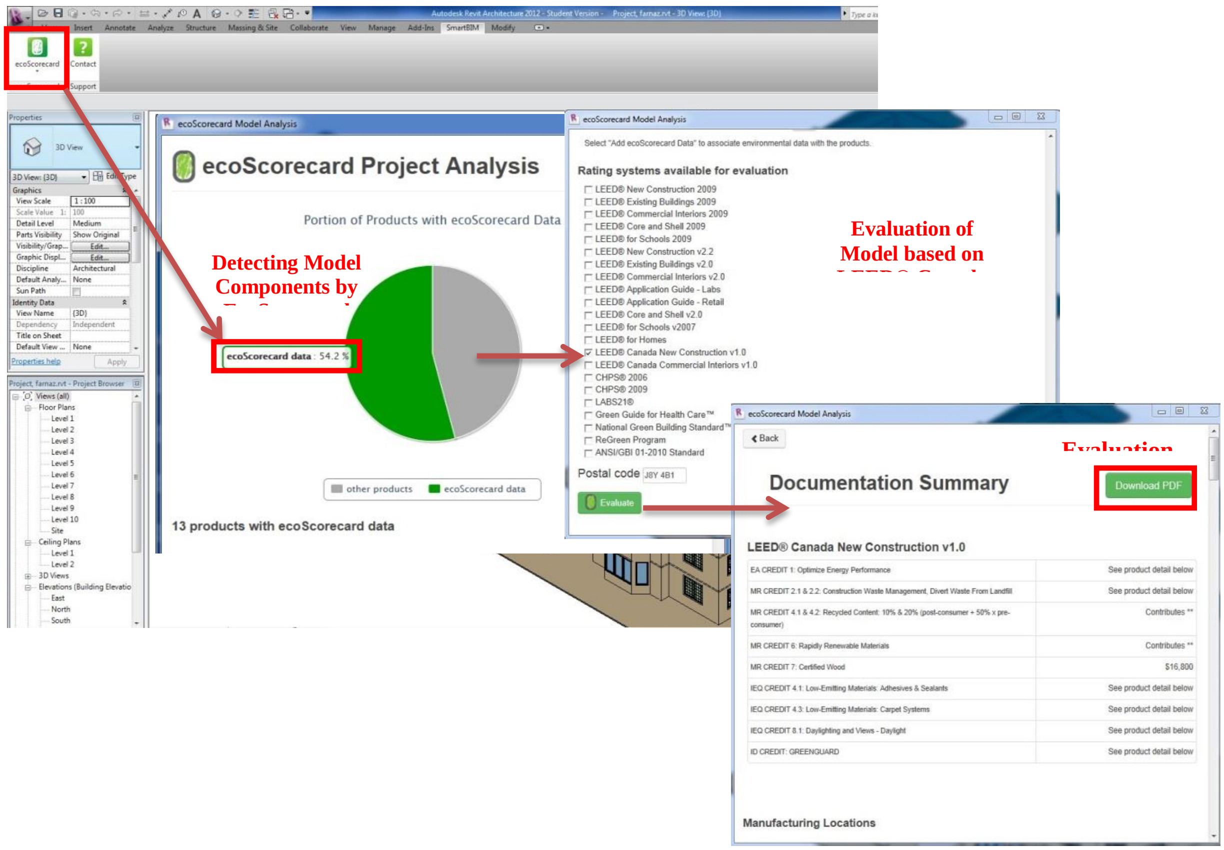

Figure 5. 10. Snapshot of using Ecoscorecard plug-in in Autodesk Revit to detect and evaluate model components based on LEED (CaGBC)

Table 5.3 shows information related to the materials and their associated potential LEED points as well as the actual points earned by the design of the case building done in Step 1 based on the results of the EcoScorecard LEED evaluation. As shown in Table 5.3, the detected components used in the design gets a total of 41 LEED points based on the CaGBC rating system. This is an approximated number of the LEED points that are earned by the designed case building since the focus of this study is at the conceptual design stage, which means the calculated points do not necessarily reflect the final number that can be earned when the building design is completed. The intent is to simply generate an idea about how many potential LEED points the proposed building might earn if a decision is made to continue the project.

Table 5. 3. Potential and actual LEED points that can be / are earned by the model

LEED-NC Credits that can be earned by each family and assembly groups using BIM-based performance analysis software			Roof		Floor		Windows		Doors		Wall	
LEED Credit	**Credit Description**	**LEED Points**	PEP	EPM	PEP	EPM	PEP	EPM	PEP	EPM	PEP	EPM
Sustainable Sites												
SSp1	Construction Activity Pollution Prevention	Required										
SSc1	Site Selection	1										
SSc2	Development Density and Community Connectivity	3,5										
SSc3	Brownfield Redevelopment	1										
SSc4.1	Public Transportation Access	3,6										
SSc4.2	Bicycle Storage and Changing Rooms	1										
SSc4.3	Low-Emitting and Fuel-Efficient Vehicles	3										
SSc4.4	Parking Capacity	2										
SSc5.1	Protect and Restore Habitat	1										
SSc5.2	Maximize Open Space	1										
SSc6.1	Storm water Design: Quantity Control	1										
SSc6.2	Storm water Design: Quality Control	1										
SSc7.1	Heat Island Effect: Non-Roof	1										
SSc7.2	Heat Island Effect: Roof	1										
SSc8	Light Pollution Reduction	1										
Water Efficiency												
WEp1	Water Use Reduction	Required										
WEc1	Water Efficient Landscaping	2,4										
WEc2	Innovative Wastewater Technologies	2										
WEc3	Water Use Reduction	2-4										
Energy & Atmosphere												
EAp1	Fundamental Commissioning of Building Energy Systems	Required								1point		
EAp2	Minimum Energy Performance	Required							*			
EAp3	Fundamental Refrigerant Management	Required										
EAc1	Optimize Energy Performance	1-19										
EAc2	On-Site Renewable Energy	1-7	*	6 points			*	8 pts			*	10 pts
EAc3	Enhanced Commissioning	2										
EAc4	Enhanced Refrigerant Management	2										
EAc5	Measurement and Verification	3										
EAc6	Green Power	2										
Materials & Resources												
MRp1	Storage and Collection of Recyclables	Required										
MRc1.1	Building Reuse: Maintain Existing Walls, Floors, and Roof	1-3										
MRc1.2	Building Reuse: Maintain Interior Non-Structural Elements	1										
MRc2	Construction Waste Management	1-2										
MRc3	Materials Reuse	1-2	*	1 point	*	1point	*	1point	*	1point		
MRc4	Recycled Content	1-2	*	1 point								1point
MRc5	Regional Materials	1-2	*	1 point	*	1point	*	1point	*	1point	*	
MRc6	Rapidly Renewable Materials	1								1point		
MRc7	Certified Wood	1							*			
Indoor Environmental Quality												
EQp1	Minimum Indoor Air Quality (IAQ) Performance	Required										
EQp2	Environmental Tobacco Smoke (ETS) Control	Required										
EQc1	Outdoor Air Delivery Monitoring	1										
EQc2	Increased Ventilation	1										
EQc3.1	Construction IAQ Management Plan: During Construction	1										
EQc3.2	Construction IAQ Management Plan: Before Occupancy	1										
EQc4.1	Low-Emitting Materials: Adhesives and Sealants	1					*	1point				
EQc4.2	Low-Emitting Materials: Paints and Coatings	1										
EQc4.3	Low-Emitting Materials: Flooring Systems	1			*	1point						
EQc4.4	Low-Emitting Materials: Composite Wood and Agrifiber products	1										
EQc5	Indoor Chemical and Pollutant Source Control	1										
EQc6.1	Controllability of System: Lighting	1										
EQc6.2	Controllability of System: Thermal Comfort	1										
EQc7.1	Thermal Comfort: Design	1										
EQc7.2	Thermal Comfort: Verification	1										
EQc8.1	Daylight and Views: Daylight	1	*	1 point			*	1point	*	1point		
EQc8.2	Daylight and Views: Views	1										
Innovation & Design Process												
IDc1	Innovation in Design	1-5										
IDc2	Accredited Professional	1										
Regional Priority												
RPc1	Durable Building	1										
RPc2	Regional Priority Credit	1-3										

Table 5.4 includes selected components used in the BIM model based on the functional, technical and financial specifications of the sustainable families collected from the manufacturers' web pages. The data provided in the functional part illustrates the capability of the materials used to provide an overall satisfaction for owners and engineers by achieving the sustainable design objectives. Generally, manufacturers provide several technical specifications for each component and family but the one shown in Table 5.4 is information related to the sustainable design factors. In reference to the financial element, the specifications shown are related to the cost of the selected components. Furthermore, it shows the most applicable criteria for the elements that have environmental friendly options. The information provided shows that the selected materials used in creating the sustainable families meet the elaborated functional, technical and financial specifications and take into consideration the environmentally friendly aspects.

Table 5. 4. Functional, technical and financial specification of sustainable materials used in the 3D BIM Model

Green Families used in the BIM sustainable model	Windows	Roof/ Ceiling	Floor	Wall	Door
Functional Criteria	-Recyclable packaging materials, -SmartTouch® Hardware PureView® Window Screen -3D®/3D MAX® Energy Packages -EdgeGar/ EdgeGard MAX™ Window Spacers -SunCoat®/SunCoat MAX® Low-E Insulating Glass -Quiet Line™ Sound Countrol Windows -Positive Action Lock	-Redirect reusable materials to appropriate sites. - Use materials with recycled content such that post-consumer plus ½ pre-consumer is at least 10% or 20%. - Use building materials or products that have been extracted, harvested or recovered, as well as manufactured, within 500 miles of the site for a minimum of 10% or 20% - Use rapidly renewable building materials and products for 2.5% of the total value of all building materials	-Products manufactured regionally within a 500 mile radius of the Project -Adhesive products must meet or exceed the VOC limits of South Coast Air Quality Management District (SCAQMD) Rule #1168 and Bay Area Air Quality Management District (BAAQMD) Reg. 8, Rule 51. - Resource Reuse - Recycled Content - Regional Materials - Use rapidly renewable building materials and products (made from plants that are typically harvested within a ten-year cycle or shorter) for 5% of the total value of all building materials and products used in the project	-Products manufactured regionally within a 500 mile radius of the Project -Adhesive products must meet or exceed the VOC limits of South Coast Air Quality Management District (SCAQMD) Rule #1168 and Bay Area Air Quality Management District (BAAQMD) Reg. 8, Rule 51. - utilize proprietary fabrication techniques for limiting waste in a controlled factory environment. - enables resource efficiencies that can often eliminate on-site waste, - reduced assembly time and smaller construction crew, - Environmental Preferable Products,	-Deliver superior energy efficiency -Help protect furniture from damaging ultraviolet (UV) rays with SunCoat® or SunCoatMAX® -Durable vinyl frames won't absorb moisture and will never need painting -State-of-the-art door rollers allow for effortless operation and adjustment of door panels -Award-winning SmartTouch® Handle - SunCoat® Low-E glass standard - EdgeGard™ spacer standard - Constructed of Recycled-content materials and contain insulating core material that does not contribute to ozone depletion.

Technical Specifications	-Exposure Category: 2000 (pa) - Air Permeability: Not more than $16m^3/h/m$ joint, : 300 (Pa) -Water tightness: no leakage: 200 (Pa) - Wind Resistance: no damage & only permissible deflection: 2000(Pa) -Design testing, manufacture and installation carried out under Quality Management Systems certified to BS EN ISO 9001.	- Finishes: PVDF (Kynar 500), MS Colorfast45®, and Acrylic Coated Galvalume® - Gauges: 24 ga standard, 26 ga and 22 ga optional - 12", 16", or 18" panel coverage, 13/4" rib height -Concealed clip (0.050" thick) designed to accommodate thermal movement - Architectural/structural integral standing seam panel -Applies over open framing or solid substrate - Factory applied side lap sealant -Snap together panel system - Minimum roof slope is 1:12 for solid substrates and 3:12 for open framing. - Reuse or salvage of ballast, Energy Guard™ roof insulation, and membrane - Material diverted from the waste stream during the manufacturing process, - Low-E glass for energy efficient performance	- Moisture Sensitive Tile or Stone-Epoxy Thin Bed with LATICRETE SpectraLOCK PRO Premium Grout -Maintain 100% of Shell/Structure and 50% in addition to Non-Shell/Non-Structure Green Floors can redeye your old carpet making it look like new. We can also refurbish your carpet floor tiles. - Divert 50% From Landfill Green Floors specialists can analyze the carpet in the building -10% (post-consumer + 1/2 post-industrial) -20% manufactured regionally	- The system allows for construction waste per home built being less than 2.5 pounds (or 0.016 cubic yards) or less of net waste per square foot of conditioned floor area. -Contain recycled content at a minimum of 25% postconsumer and 50% post-industrial for at least 90% of the building component. - Concrete or Masonry Wall (Exterior)-Thick Bed Over Metal Lath with LATICRETE PermaColorTM Grout	- Provide aluminum top track, side jambs, and vertical struts: White powder coated or clear anodized or dark bronze anodized or powder coated select from range of RAL powder coated finishes available from manufacturer. -Light to Solar Gain Ratio: 2.0 - Solar Heat gain Coefficient: 0.15 - Visible Transmittance: 0.54 - PEFC™ Certified: 70.0% - ISO 14001 Voluntary Environmental Management Systems - ENERGY STAR® Listed - National Fenestration Rating Council Certified -Interior doors are typically constructed of wood products (veneer, core materials, and styles) and synthetic wood products (plastics).
Financial Investments	Minimise disturbance of the existing structure and internal finishes to a minimum, thereby reducing the cost of making good.	This roof was selected because of its engineered cooling attributes for a cooler roof and a projected cooling cost saving of 20%.	lowers maintenance costs a minimum of 10% (based on cost) of the total material value	Benefits accrue well beyond the design and construction budget through energy savings, a reduction in the contributory costs of the built environment to global warming	The cost is higher than for conventional doors. Such cost increases are dependent on the sustainable features specified.

Since not all suppliers provide the cost of products on their website, authors used RS-Means cost data to prepare preliminary cost estimate for the case building as shown in Table 5.5. In this table, the total estimated cost of each building component is calculated using the R.S. Means Green Building Cost database. In this database the unit cost of each family is calculated based on the year 2013 national average value and adjusted for the city of Ottawa. To prepare the cost estimate, materials with specifications similar to the quantity take off extracted from the developed 3D design are selected from the R.S. Means database. However, as illustrated in Table 5.5, the preliminary cost estimate of the building components using the proposed method is calculated to be $1,621,834.79 while the actual estimated cost was calculated to be $1,889,186.39 for the year 2013 which reflects a 17% difference in the values, which is acceptable for the conceptual stage where little information about the project is known.

Table 5. 5. Associated cost of the selected components based on R.S. Means cost data

Description (Green Building)	Unit	Quantity	Total Unit Cost ($)	Total Item Cost ($)	Description (Typical Building)	Total Unit Cost ($)	Total Item actual Cost ($)
Windows							
Windows, wood, sliding, vinyl clad, premium, double insulated glass, 6'-0" x 5'-0", incl. frames, screens & grill	Ea.	100	$1,078.00	$107,800.00	Windows, aluminum, awning, insulated glass, 4'-5" x 5'-3"	$58.64/ SF	336,300.4
Windows, wood, casement, average quality, builder's model, double insulated glass, 2'-4" x 6'-0" high, incl. frame, screens and grilles	Ea.	48	$ 431.65	$20,719.00			
Roof							
Wood shingles, white cedar, 3/4" thick x 16" long, 5" exposure on roof	Sq.	777	$303.79	$236,044.83	Wood shingles, white cedar, 3/4" thick x 16" long, 5" exposure on roof	$386.92	300,636.84
Floor							
Resilient Flooring, cork tile, standard finish, 5/16" thick	S.F.	40,849	$12.43	$507,760.00	Floor, concrete, slab form, open web bar joist @ 2' OC, on W beam and wall, 25'x25' bay, 26" deep, 75 PSF superimposed	$14.91	609,058.59
Doors							
Doors, glass, sliding, vinyl clad, 5'-0" x 6'-8" high, 1" insulated glass	Ea.	8	$1498.88	$11,991.04	Door, aluminum & glass, with transom, narrow stile, double door, hardware, 6'-0" x 10'-0" opening	$7.72/ ft^2	$72,500.00
Doors, glass, sliding, aluminum, premium, 5/8" tempered insul. glass, 6'-0" x 6'-8"	Ea.	15	$1567.58	$23,513.70			
Walls							
Precast wall panel, smooth, gray, un-insulated, high rise, 4' x 8' x 4" thick, 3000 psi	S.F.	16250	$37.62	$611,325.00	Brick walls,13.5 brick per square foot, 8" thick wall, includes mortar, 8% brick waste and 25% mortar waste, vertical reinforcement and grout, excludes scaffolding & horizontal joint reinforcement	$29.97	487,012.5
Railing & Stairs							
Stair, shop fabricated, steel, 3'-6" W, including picket railing, stringers, metal pan treads, excl concrete for pan treads, per riser	Riser	158	$519.83	$82,133.14	Stairs, steel, cement filled metal pan & picket rail, 16 risers, with landing	$5.27/ ft^2	83,678.06
Railing, pipe, steel, primed, 3 rails, 3'-6" high, posts @ 5' O.C., 1-1/4" diameter, shop fabricated	L.F.	453	$45.36	$20,548.08			
Approximated Construction Cost	**$ 1,621,834.79**			**Actual approximated cost**		**$ 1,889,186.39**	

5. 6. CONCLUSIONS

The intent of this research at the conceptual stage is to help decision makers generate a better idea about the project while making important decisions related to the continuation or dismissal of that project. Though the level of accuracy of the available information at that stage is low, nevertheless decisions have to be made. Thus, any additional information would be an asset and helpful to support the decision. The novelty highlighted in this paper describes the model's different modules, which are integrated into each other based on an automated process by creating new plug-ins and improving the functionality of the existing ones so that users will be able to start the sustainable design of a proposed building project at the conceptual stage of its life in a timely and cost-effective way. Using a BIM integrated platform moves the design decisions forward at the early stage especially when comparing different design alternatives, which is considered to be an attribute of this research.

The developed model enables users to compare and select different materials and components, which are stored in the external database, to be used in their design based on energy and sustainability specifications and costs. This accelerates the process of modifying building components early in the conceptual design stage in the case that the selected ones do not meet owners or designers requirements. The BIM model created is successfully imported into ECOTECT with gbXML and IFC file formats by using the developed plug-in in Revit. The mapping to gbXML is shown to contain more of the data needed for energy analysis and in this project is the preferred format to use during the conceptual design stage. Furthermore, the developed database was designed based on collected information that contained a limited number of certified components, all of which are designed and provided by the manufacturing companies. This is a limitation for the model because it does not cover all the existing green elements and, as was previously mentioned, only 54.2% of those materials and components were detected and defined in the Ecoscorecard database. This means that there are several green families that need to be designed, converted to BIM file format and added to the database. Missing information during the transformation process from the BIM tool to the other tools (i.e., energy analysis and simulation) includes the information required as input by different software. Some information needs to be entered manually by the user after the transfer process, while other types of information are automatically assumed by the software itself (i.e. information about the type of materials when transferring from Revit to Ecotect or IES-VE).

In this research, different energy tools have been used and their results have been compared. While Ecotect gives annual thermal consumption and peak loads for worst-case times, the IES Apache Simulator gives comprehensive information about the total annual energy consumption and room loads. The variation in Ecotect in terms of the heating and cooling loads is due to the calculation method used by this tool. Ecotect uses the worst design annual load case while the ASHRAE load calculator built into IES uses the worst monthly scenario (January) for heating loads and a five-month long (May-September) scenario for cooling loads. The discrepancy in the results between Revit, IES and Ecotect was expected to occur because of the different load calculation techniques, calculation engines, and variation in the materials types and their associated values found in these tools.

In the developed model, multiple design alternatives are compared through the economical aspect. The results generated by the different modules are evaluated based on diverse economical perspectives. Energy analysis results are good feedback to the design team about the potential energy that can be gained or lost within a year by the proposed building. Using these data can ease the way of estimating the energy cost which is a major part of the operation cost for any building. Compared to the traditional way of making building estimates, Life Cycle Cost can take environmental impact and the energy aspect into account, which will have a big effect on future capital variable. Along with the obvious environmental advantages, LEED-certified buildings cost less to operate and are more desirable for commercial and residential occupants. In the integration platform, the process of having this information is done in a timely manner and it is done easily by clicking on the developed plug-ins and using the connected database.

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CHAPTER 6

TECHNICAL PAPER III

An automated BIM model to conceptually design, analyzes, simulate and assess sustainable building projects

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Abstract- Presently the construction industry is more interested in designing and constructing environmentally friendly buildings (e.g. sustainable buildings) that can provide both high performance and monetary savings. For years, energy simulation tools were used by designers to design energy-efficient buildings. Quantify the environmental impacts and simulating the energy consumption of a building's components at the conceptual design stage is very helpful for designers needing to make decisions related to the selection of the best design alternative that would lead to a more energy efficient building. Incorporating these components at the conceptual stage is achieved by using sustainable design, through which designers must identify associated materials and systems based on any selected certification (rating) system. Building Information Modeling (BIM) offers designers the ability to assess different design alternatives at the conceptual stage of the project so that energy and Life Cycle Assessment (LCA) strategies and systems are attained. Furthermore, BIM allows designers to select the right type of materials during the early design stage and to make energy related decisions that have great impact on the building's life cycle.

The aim of this paper is to propose a fully automated model that links BIM, LCA, energy analysis and lighting simulation tools with green building certification systems. The successful development of the methodology will provide owners and designers with a tool that can be used to evaluate different design alternatives within the constraints of sustainability in an efficient and timely manner. The implementation of the automating process is within developing plug-ins on BIM tool capable of measuring the Environmental Impacts (EI) and embodied energy of every

building component used in the BIM model. Using this method, designers will be provided with a new way to visualize and to identify the potential gain or loss of energy for the building as a whole and for each of its associated components. Furthermore, designers will be able to detect and evaluate the sustainability of the proposed building's BIM model based on Leadership in Energy and Environmental Design (LEED) rating system so that they can modify their sustainable conceptual design in a more efficient way. An actual building project will be used to illustrate the workability and capability of the proposed methodology.

KEYWORDS: BIM, Energy Analysis and simulation, Green Building, Certification System, LEED, LCA, Sustainable Design

6.1. Introduction

Important decisions related to the design of sustainable buildings are made at the conceptual stage of their lives. This practice does not consider the integration between the design and energy analysis processes during early stages and leads to an inefficient way of backtracking to modify the design in order to achieve a set of performance criteria (Schueter et al., 2009). Energy efficiency is an important feature in naming building materials as being environmentally friendly. The ultimate goal in using energy efficient materials is to reduce the amount of artificially generated power that must be brought to a building site (Jong et al., 2010). Generally, building materials consume energy throughout their life cycle starting by the manufacturing stage, passing through that of use and finishing by the deconstruction phase. These stages include raw material extraction, transport, manufacture, assembly, installation as well as disassembly, deconstruction and decomposition. The total life cycle energy of a building includes both embodied energy and operating energy (Crowther, 1999). Embodied energy is sequestered in building materials during all processes of production, on-site construction, transportation, final demolition and disposal. Operating energy is expended in maintaining the inside environment through processes such as heating and cooling, lighting and operating appliances.

Presently, Building Information Modeling tools have the ability to provide users with an opportunity to explore different energy saving alternatives at the early design stage by avoiding the time-consuming process of re-entering all the building geometry and supporting information necessary for a complete energy analysis. Using BIM helps owners and designers make energy related decisions that have a high impact on the proposed building life cycle cost at the early stage of design. Krygiel and Nies (2008) indicate that BIM can aid in the aspects of sustainable design which include: building orientation, building massing (that is used to analyze building form and optimize the building envelope), day lighting analysis, water harvesting (that is used to reduce water needs in a building), energy modeling (that helps reducing energy needs and analyzing how renewable energy options can contribute to low energy costs), sustainable materials (that helps reducing material needs by using recycled materials) and site and logistics management (to reduce waste and carbon footprints).

Hoff (2008) describes EI as being the result of the inputs and outputs over a product's life cycle. Although the total number of different potential EIs may be very large, the U.S. Environmental Protection Agency has categorized the "top ten" impacts as: 1) Global Warming Potential, 2) Ozone Depletion Potential, 3) Photochemical Oxidant Potential, 4) Acidification Potential, 5) Eutrophication, 6) Health Toxicity (Cancer), 7) Health Toxicity (Non- Cancer), 8) Health Toxicity (Air Pollutants), 9) Eco-Toxicity Potential, 10) Fossil Fuel Use. Thus, to quantify the impacts of the selected materials on the environment, an assessment method has to be applied. The common method employed is LCA, which is a tool used for evaluating environmental concerns (Khasreen et al., 2009). It is because of this that designers must keep the entire life cycle of the building and its associated materials in mind. This will promote sustainable development practices through suited rating systems by recognizing the projects that implement strategies for better environmental and health performance (USGBC, 2011). Furthermore, linking BIM with LCA tool supplies users with information related to the embodied energy needed for every single component present in the proposed building and, accordingly, allows them to select the best components at the conceptual design stage.

Usually, using BIM tools to design sustainable buildings necessitates the selection of materials and systems whose embodied energy can be easily evaluated. Thus, the common method used to quantify the embodied energy of the selected materials is LCA. For this purpose, designers use LCA tools to model, to modify, and to input energy simulation results and calculate the embodied effects of their design. Hence, it will be necessary to evaluate and to compare the capabilities of these file formats in exchanging information between BIM and LCA tools, which are highly important for designers who need to transfer the design information directly from the

BIM model to the energy analysis software. Yet, using BIM tools to design sustainable buildings necessitates the selection of materials and systems so that their EI and embodied energy can be easily evaluated. Thus, the common method used to quantify the EI and embodied energy of the selected materials is LCA. For this purpose, designers can use "The Impact Estimator for Buildings", which is a stand-alone tool that allows users to model their own custom assembly and envelope configurations and provides them with the flexibility to modify the proposed designs and existing buildings. Hence, the main objective of this paper is to automate the integration process of BIM, LCA and energy analysis and simulation tools to design sustainable buildings. This assimilation will also include the sustainable design for proposed buildings at the conceptual stage in an attempt to help owners and designers analyse the day lighting and measure the thermal of such types of buildings. To make this integration fully automated, authors developed plugs-in in BIM tool to enable users transfer their design information directly from the BIM model to the energy analysis software. In this way, users can easily export the materials' quantity take offs and connect them to other tools such as the LCA tool so that designers can have relevant information about the EI and embodied energy for associated components of the designed building at the conceptual stage. Access to said information will then allow them to determine and correct potential problems.

Furthermore, designers are able to evaluate the sustainability of the building components used in the BIM model by using another plug-in in BIM tool which supports suppliers' web pages by cataloguing green components and products and their environmental characteristics. In addition, by assigning the unit cost of every building component in BIM tool, design team is able to create supportive documents such as initial cost estimation of the BIM model. Using the proposed automated process at the conceptual stage of the project enables designer to determine which products best meet their needs, evaluate them based on optional environmental rating systems, and print the necessary documents in an easy, quick and convenient way.

6.2. Literature review

Building Information Modelling (BIM) is gaining popularity in the building industry where it was first coined over ten years ago to distinguish the 3D modelling rich information from traditional 2D drawings. Currently, BIM is widely adopted by the building industry due to its ability to correct mistakes at the early stages as well as aid in accurately scheduling and sequencing the construction , identifying conflicts and advocating design alternatives and facilitating the selection of appropriate solutions for complex projects (Kubba, 2012, Azhar, et al, 2011). Based on Kubba (2012) and Becerik-Gerber & Rice (2010), development of a schematic model prior to the generation of a detailed building model, allowing the designer to make a more accurate assessment of the proposed scheme and evaluate whether it meets the functional and sustainable requirements set out by the owner; this helps increase project performance and overall quality. The advent of BIM along with the emergence of global challenging issues like sustainability, and life cycle cost of buildings, necessitates designers to incorporate the basic performance analysis from an early design phase. That is special quality analysis, energy performance, social impact and environmental performance into its framework by further developing the concept of virtual space and virtual building (Kam et al., 2004). An integrated BIM system can facilitate collaboration and communication processes between project participants in an early design phase to effectively provide a well performing building during operations. (Hungu, 2013)

Combining sustainable design strategies with BIM technology has the potential to change the traditional design practices and to efficiently produce a high-performance design of proposed buildings. BIM technology can be used to support the design and analysis of building's systems at the early design process. These include the experimental structural analysis, the environmental controls, the construction method, the selection of new materials and systems and the detailed analysis of design processes. The building system analysis involves many functional aspects of the building system such as structural integrity, ventilation, temperature control, circulation, lighting, energy distribution and consumption (Azhar et al., 2010). Hence, an ideal opportunity exists for the sustainability measures and performance analysis to be integrated within the BIM model (Azhar et al., 2009). BIM includes associated benefits of visualization, built-in intelligent objects of a building model such as spatial data (3D), unstructured data (text), and structured data such as spreadsheets and databases. BIM models not only provide data pertained to the building geometry but they allow the calculation of volumes and related energy based on the building's characteristics and orientation.

Energy analysis is typically performed after the architectural/engineering design and related documents have been produced. This practice does not consider the integration between the design and energy analysis processes during early stages and leads to an inefficient way of backtracking to modify the design in order to achieve a set of performance criteria (Schueter and Thessling, 2009). For the past 50 years, a variety of building energy simulations and analysis tools have been developed, enhanced and applied throughout the building industry. Examples of these tools are BLAST, EnergyPlus, eQUEST, TRACE, DOE2, Ecotect and Integrated Environmental Solution (IES-VE) (Crawley et al. 2005). Grobler (2005) claimed that building designs (conceptual and detailed) affect the construction and operation costs of a building. Several researchers describe energy analysis as a holistic evaluation (Abaza, 2008). Dahl et al. (2005) and Lam et al. (2004) show that decisions made early in a project have a strong effect on the life cycle costs of a building. Simulation tools, such as Integrated Environmental Solution-Virtual Environment (IES-VE) and Ecotect, are able to conduct comprehensive building performance analysis, including energy simulation. IES has direct interaction with BIM tools such as Autodesk Revit. Ecotect is a building design and environmental analysis tool that covers a broad range of simulation and analysis functions required to understand how a building design will operate and perform. It allows designers to work easily in 3D and to apply tools necessary for an energy efficient and sustainable future. Some of its features include a shading design and solar analysis, lighting analysis, acoustic analysis, thermal analysis, ventilation and air flow analysis, building regulations and resource management. Ecotect does not have a plug-in in BIM tools, therefore the way it can get connected with BIM tools is through file format exchanges.

Jalaei and Jrade (2013) evaluated and compared the capabilities of different file formats in transferring information from BIM tool into energy analysis and simulation applications. The result of this validation showed that gbXML has a simplified schema for energy analysis, although that when preparing an analytical model from BIM 3D model to be imported via gbXML file format is time-consuming for large and complex projects, it is currently a preferred format during design development or the schematic stage. The green Building XML schema — commonly known as “gbXML” — was developed to facilitate the transferring process for the information stored in building information models to enable the integration and interoperability between the design models and other engineering analysis tool (Kumur, 2008). However, gbXML also facilitates the exchange of the building information (which includes product characteristics and equipment performance data) between the manufacturer’s database, the BIM models and the energy simulation engines. One of gbXML’s benefits is its ability to carry detailed descriptions of a single building or a set of buildings which can be imported and used by energy analysis and simulation tools.

When creating sustainable designs, designers are concerned about their ability to evaluate the EI of the selected materials and components by using available methods and tools. In this perspective, the idea of LCA has emerged as the collection and evaluation of the building inputs and outputs and the potential energy of a product throughout its life cycle (Guinée et al., 2011). While LCA can be used to assess the sustainability of the built environment, its technique provides comprehensive coverage of the product’s energy consumption, as such it is very useful to apply it to the conceptual design phase of building projects. At that stage the designer must be able to acquire, store, and organize LCA data for the components in such a way that it can be used to generate feedback during the design process (Ries and Mahdavi, 2001).

In order to analyze the EI as well as embodied energy of buildings’ components, a methodology that integrates BIM models with LCA systems is needed due to its potential to streamline LCA processes and facilitate the rigorous management of the environmental footprint of constructed facilities. Jrade and Jalaei (2013) describe a methodology emphasizing the integration of BIM, Management Information System and LCA that can be used to implement sustainable design for proposed buildings at their conceptual stage all the while taking into consideration their Environmental Impacts. Häkkinen and Kiviniemi (2008) identify the following solutions to integrate BIM tools with LCA systems: 1) linking separate software tools via file exchange, 2) adding functionality to existing BIM software and 3) using parametric formats such as Geometric Description Language (GDL). Until recently, only operating energy was considered, owing to its larger share in the total energy life cycle. However, due to the advent of energy efficient equipment and appliances, as well as more advanced and effective insulation materials, the potential for curbing operating energy has increased and, as a result, the current emphasis has shifted to include embodied energy in the building materials (Crowther, 1999; Nassen et al. , 2007). Thus, there is a genuine demand for measures to calibrate the performance of buildings in terms of both embodied and operating energy in order to reduce their energy consumption (Langston et. al, 2008; Treloar et. al., 2001). Transport energy is a function of material’s weight, transport method and the travelled distance. From these three factors a reasonably accurate calculation of the transport embodied energy can be done.

While green building certification systems can be used as guidance for design, to record performance progress, to compare buildings and to document the outcomes and/or strategies used in the building (Wang et al., 2012), different types of methodology such as Building Research Establishment Environmental Assessment Method (BREEAM) (Baldwin R et al., 1998), Green Star from Australia (GBCA, 2008), and the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) from Japan (CASBEE, 2008) have been developed. More locally, we can also find the Building and Environmental Performance Assessment Criteria (BEPAC) from Canada (Cole et. al., 1993) and the Leadership in Energy and Environmental Design (LEED) from the United States (USGBC, 2011). All of these methodologies are widely used to establish the environmental goals' level of achievement and to guide the planning and design processes. Furthermore, comprehensive tools for environmental assessment can be found (Ding, 2008) such as the whole Building Design Guide (WBDG, 2012) and the World Green Building Council (WGBC, 2008).

Although these tools have an extended use, the LEED Rating System (LEED-RS) has established a strong credibility among the experts (Pulselli et al., 2007). The LEED-RS was evaluated to its importance as a measurement tool for the environmental performance of a building by 7,500 companies and organization members around the world. Yet, in order to automate the evaluation of the environmental specifications of the proposed building model in BIM at the conceptual design stage, designers can use sustainability evaluator tool (i.e. EcoScorecard©), which is a plug-in to BIM tool. This Plug-in has the ability to evaluate and to document the environmental data for various rating systems such as those of the US Green Building Council "USGBC", the Canadian Green Building Council "CaGBC", the Collaborative for High Performance Schools (CHPS) and the National Green Building Standard (NGBS) as well as other third-party product certification systems. LEED Canada-NC 1.0 (NC standard for new construction and major renovations) is the Canadian version of the LEED certification system. It is approved by the USGBC and was released by the CaGBC in December 2004. An addendum to LEED Canada-NC 1.0 was developed in 2007, which included improved requirements introduced by the USGBC for LEED-NC 2.2, along with other improvements related to the durable building credit. The CaGBC is the source for these LEED reference information and updates, including templates.

Despite that lots of efforts have been put in place toward the advancement of sustainability, still the energy efficiency and its resulting values besides the corresponding cost savings are not key criteria in the building development process. Energy and performance analysis are typically performed after the architectural design and construction documents have been produced. This lack of integration into the design process leads to an inefficient process of retroactively modifying the design to achieve a set of performance criteria. The importance of incorporating all disciplines from the early stages of design is widely acknowledged and documented (Bouchlaghem et al., 2005). Early decisions are crucial in order to achieve sustainability objectives in the resulting design outcome (Schlueter et al. 2009). According to Eastman et al. (2008), developing a parametric model within the BIM environment is capable of capturing project information and generating documentation. With special care taken on the software side, an enhanced BIM application could potentially resolve what used to be major problems in the delivery of sustainable design (i.e. dealing with the complexity of conducting a full building energy simulation, acoustical analysis, and day lighting design). The authors are not able to find in the literature any research that looked at the possibility of having the design team to have access to different types of information such as energy consumption, environmental impacts and embodied energy of every building component, pursued accumulated green building rating system points and associated costs all within a BIM environment, while the conceptual design is in progress. Although the potential of using BIM models for energy simulation is well known, a systematic approach that can be used to share the necessary information is still lacking (Young, et al. 2009). The data related to the buildings internal loads such as occupancy and lighting should be included in the data exchanging process between BIM tools and energy simulation software in order to avoid any repetitive data inputs (Pimplikar and Esmaeili, 2012). To pursue the integration procedure is to test the data inputs and outputs using different interoperable formats and to select the more efficient one. Since the automation process will take place at the conceptual stage of a project life while doing sustainable design, another aspect of this study is to use an application to evaluate the created model in order to get details about its environmental and sustainability specifications in a systematic way. In this case, users can add up the potential points that can be earned during the design based on the selected green building certification system. This would provide the design team with the opportunity to analyze energy results for the whole model as well as EI and the embodied energy of every component. Autodesk Revit®, which is used as BIM tool in this research, provides the opportunity to create custom tools that plug directly into Autodesk Revit®. This would extend the functionality of the BIM tool and would allow users make well-informed decisions in selecting optimum sustainable building components.

6.3. Scope and significance of the study

This paper describes a methodology to implement an automated and integrated platform to do sustainable design for proposed buildings at their conceptual stage. The methodology is implemented through the design and development of a model that simplifies the process of designing sustainable buildings and hence of transferring the design information to energy analysis tools so that designers can implement energy and lighting analysis. The model has also the capability of listing the certification points that can potentially be earned based on the selected system for sustainability. The methodology incorporates an integrated model capable of guiding users when performing sustainable design for building projects. It incorporates five modules: 1) Database Management System (DBMS), 2) BIM, 3) Energy and lighting analysis, 4) Life Cycle Assessment (LCA), and 5) LEED and cost. The major task of the model is to expand, develop and collect lists of green products and certified materials, these materials will be linked to the BIM tool. Part of this integrated methodology is to develop plug-ins and customize the available ones in BIM tool so that users can connect their design module with other modules in an efficient and consistent manner. The objectives of this study are listed as follow:

• Collect and store series of design families that incorporate sustainably certified components in a database in an attempt to improve the workability and capability of the BIM tool used to do sustainable design at the conceptual stage.

• Create and develop a framework for this integration that considers the sustainable design requirements and the functionality of BIM tool,

• Investigate the feasibility of implementing a full integration between BIM and Energy (operational and embodied) and lighting analysis tools,

• Develop the automated BIM model that integrates the abovementioned five modules and then validate it by using an actual existing building project to test its workability and capability.

Afterwards, analyze the information associated with the case project to identify how much was transmitted during the transformation process between the different tools.

One contribution of this research is the ability to measure the transport energy, which is one significant component of the embodied energy used to transfer materials and building components from suppliers' location to the building site. IE tool does not recognize this type of energy and accordingly it does not have the capability to calculate it.

Different types of software commonly used in the construction industry, such as Autodesk Revit Architecture©, Autodesk Ecotect, Integrated Environmental Solutions (IES-VE), Microsoft Excel© and Athena® Impact Estimator© were used in the development of the proposed model.

6.4. Methodology and Model Development

The aim is to develop an automated way in which 3D sustainable design of a proposed building project is accomplished and related energy analysis and simulation results of the whole building and every one of its components identified. Since the proposed methodology integrates different applications, as is represented in Figure 6.1, the development will be implemented through the following six phases:

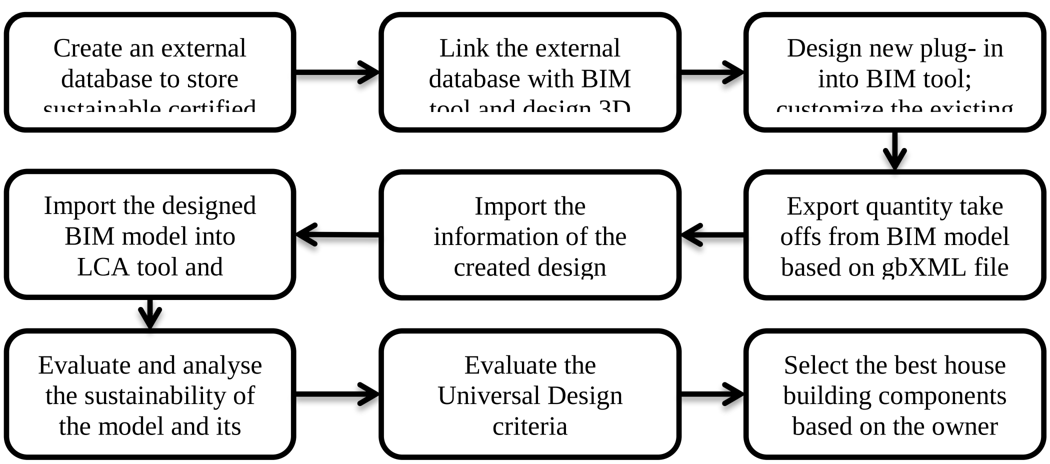

Figure 6. 1. Methodology of the integration system

Phase 1 consists of designing the model's relational database needed to design sustainable building. Loucopoulos (1992) states that a consistent information system depends on the integration between databases, programming languages and software engineering and its lifecycle incorporate the interrelated technologies of conceptual modeling and database design. The design and development of this database is accomplished in two steps starting by the conceptual modelling and ending by the physical implementation. The information related to the green materials is stored in an external database in the form of predefined design families that can be recognized by BIM tool. The aim of developing a separate database is to have it loaded every time the BIM tool (Revit) opens by defining its path that is linked to the predefined library of Revit. The data related to the green materials is saved as family files (RFA) or Revit files (RVT), which can be identified by the BIM tool. Thus, in the external sustainable database, up to 3,000 design families are collected from the literature, suppliers' web pages, USGBC and CaGBC websites as well as published data and are arranged based on the 16 divisions of the Masterformat WBS. Different types of information such as details about the materials used, suppliers' contact data, assigned keynotes, potential LEED criteria and assembly codes are stored in the external database.

Phase 2 focuses on customizing BIM tool to fit the modularity requirements of the model. The first step is to design and implement a 3D module capable of storing newly created families, in BIM tool, and their associated keynotes for components commonly used in residential buildings by using certified green materials. The module is linked to the database developed in Phase 1. Keynotes are textual annotations that relate text strings to specific elements in the model, which are in turn linked to an external text file. It can be used as external link to the element itself with specific style and specifications so it can be used as a Revit family. That means, user can insert different text family types in Revit. Keynotes can be assigned to elements which are typically used if the user wants to note an entire assembly, such as a wall assembly. The sixteen Masterformat divisions present the main WBS applied in this research. It is very important to select a unique code for each item that is presented in a separate line in the database to ease and simplify their usage.

Phase 3 focuses on creating a plug-in, which is a type of algorithm that adds functionality to the BIM tool by integrating it with the energy analysis and simulation tools. Plug-In or Add-In are terms used in BIM tool to signify a module containing an algorithm that makes use of the BIM tool's Application Program Interface (API). The BIM tool used in this study has a .NET API, which means that any of the .NET compliant programming languages (C#, VB.NET, F#, etc.) can be used to develop a customized plug-in. While each language has its own relative benefits, C# has been used in this research due to its simplicity, usability and powerful ability to underlay the .NET framework. Table 6.1 represents sample of the developed algorithm used to export the materials quantity take offs to energy analysis tool based on gbXML format. This algorithm uses C# programming language, which is used in developing the plug-ins that will be applied to the BIM tool.

Table 6. 1. Sample of the algorithm developed to transfer the material quantity take-offs from BIM model to energy analysis tool

Integration Algorithm used to create plug-in	**Task**

//GBXMLExportOptions gbx = new GBXMLExportOptions();
//Transaction t = TransactionManager.StartTransaction();
Transaction t = new Transaction (doc);
t.Start("gbXML based export plug-in");
doc.Export("c:\\1\\ ", "gbxml", newGBXMLExportOptions());
t.Commit();
//doc.SaveAs("gbxml.xml", sao.OverwriteExistingFile);
Process notePad = new Process();
	Export and save material Quantity Take offs to gbXML format

notePad.StartInfo.FileName = "Ecotect.exe"; notePad.StartInfo.Arguments = "C:\\1\\gbxml.xml"; notePad.Start();	Call Ecotect.exe to open gbXML files from the place it is already saved

Phase 4 consists of designing energy analysis and simulation modules that help exporting the 3D design created in BIM tool as gbXML file format. The energy analysis tools used in this research is Ecotect, due to its efficiency in evaluating the thermal and solar gains for the architectural designs of proposed buildings. It easily creates or cleans up models in a format that includes both the geometry and the zones of a building, besides having interoperability potentials with other tools. This interoperability makes it an ideal tool to import and export the 3D design between BIM tools, which generate the geometry of the proposed building, and different energy analysis tools. IES-VE contains an Integrated Data Model that captures all the information related to the proposed building including the geometric data, which is needed to do all necessary analyses. Yet, it must be said that the 3D geometric information can also be imported straight from the BIM tool using gbXML file format. Constructions materials can also be selected from the IES-VE built-in database, which is known as the Apache construction database.

Phase 5 concentrates on designing LCA modules that interconnect the 3D BIM design with the LCA tool through an ODBC exporting format, which directly transfers the materials' quantity take offs to any file format in an attempt to evaluate their environmental impacts. The LCA tool is linked to an external database, which is in turn associated with the BIM module that stores the extracted quantities of materials from the 3D design and evaluates their EI as well as embodied energy. The extracted bill of quantity is then linked to ATHENA® Impact Estimator© in a text exchange file format. Authors elected to use ATHENA Impact Estimator for Buildings because it is commonly used by the North American construction industry and because it is designed to evaluate the whole building and its assemblies based on the internationally recognized life cycle assessment (LCA) methodology.

Lots of materials are delivered to the site by rigid trucks, thus to calculate the transportation Energy, the developed model considers this as one of the inputs stored in the database developed in phase 1. To ease the development process of this module a framework is created.

Transportation embodied energy is dependent on the type and number of trucks, the travel distance between suppliers and construction site, and material properties (i.e. size and weight). In order to demonstrate the model's capabilities, four different types of trucks (as listed in Table 6.2) are taken into account when identifying the required number of trucks. In this study, a gross vehicle weight (GVW) is considered as the maximum weight value of a vehicle that includes weight of a vehicle and cargo and a payload is defined as the total weight of all cargo that a vehicle carries. Also, the size of the load in the truck bucket is limited to 53×13.5×8.5 ft (L×H×W) (Irizarry et. al, 2013). Using the properties identified above and quantity of material for a given order, the required number of trucks can be determined. The proposed algorithm selects combination of trucks based on the minimum value of fuel consumption. Then, the fuel consumption value is calculated according to the traveled distance per unit of fuel used in miles per gallon (MPG). The distance measurement can be done by using the geospatial method used by BIM tool that specifies the geographic location for the project. It uses an Internet mapping service to visualize the project location by searching its street address, or the longitude and latitude of the project.

Table 6. 2. Descriptive attributes for each type of trucks selected for the case building

Truck Type	GVW (lb)	Payload (lb)	Fuel Consumption (MPG)	MPG for empty truck
1	36,300	25,300	-0.0246W+6.63	6.62
2	60,600	40,800	-0.0258W+6.285	6.26
3	80,000	55,750	-0.0255W+6.205	6.18
4	92,000	66,200	-0.0263W+5.885	5.86

W=Total Weight of Load (1000xlb).

Phase 6 includes the design and development of a green building certification and cost estimating module, which is linked to the BIM. This module contains data collected from the suppliers and publishers webpages, which are retrieved from the created model by using the sustainability evaluator plug-in that is loaded into BIM tool. Authors collected information about sustainable materials and components from the manufacturers and vendors websites as well as using the smart BIM green components, which can be detected by the sustainability evaluator. In the sustainability evaluation results, there is detailed information about every component, which includes the potential LEED points that can be gained if these materials or components are used in the design. This information is stored in the external database of the BIM tool. Therefore, when designers model the design for a proposed building project in 3D and select any of these sustainable materials or components, the potential LEED points gained by these selected items are identified and stored in the schedule associated with the model. Afterwards, users will add up these LEED points to identify the potential number that the proposed building can earn and accordingly its potential level of certification (Certified; Silver; Gold or Platinum). Furthermore, the associated cost will be generated by linking the model created in BIM tool with the cost module, which is linked to the database that stores information about green and certified materials. The associated cost of the developed design is then calculated based on R.S. Means published data.

6.5. Model Application

The development of the model described in this paper focus on automating the process of connecting the output of BIM module with other different modules. The developed model is an integrated tool that helps owners and designers share variety of information at the conceptual design stage of sustainable buildings. It assists designers in comparing and evaluating each design family and its associated components that is selected during the conceptual design taking into consideration the materials' selection criteria.

Figure 6.2 shows a flowchart of the integration process that is used in this study. It determines the processes applied to the design created in BIM tool while considering all related criteria and specifications based on the described phases. Figure 6.3 illustrates the model's architecture when the input section includes the certified components stored in the database, based on the Masterformat WBS, containing keynotes and families as well as suppliers' information. Project orientation and the specified green building rating system for sustainability analysis are identified as inputs. The criteria section includes the green building rating system as well as the environmental performance and principles to select green materials. The main output of the model will be a sustainable design in 3D mode of the proposed building that includes lists of the selected sustainable materials and their environmental impacts as well as the results of the energy simulation and daylight data analysis. This platform provides a suitable environment to establish a Decision Support System (DSS) to help design team decides on the selection of the most appropriate type of sustainable building components and families for proposed projects based on defined criteria (i.e. Energy consumption, Environmental impacts and Economic properties) in an attempt to identify the influence of the design variations on the sustainable performance of the whole building. The final design will be influenced by the results of the energy and lighting analysis, the LCA and Environmental Impact and embodied energy results, and the sustainability evaluation of every building component based on LEED rating system besides the initial costs of these components. These results represent a reasonable perspective to evaluate how far the design deviates from the standards and owners' expectation.

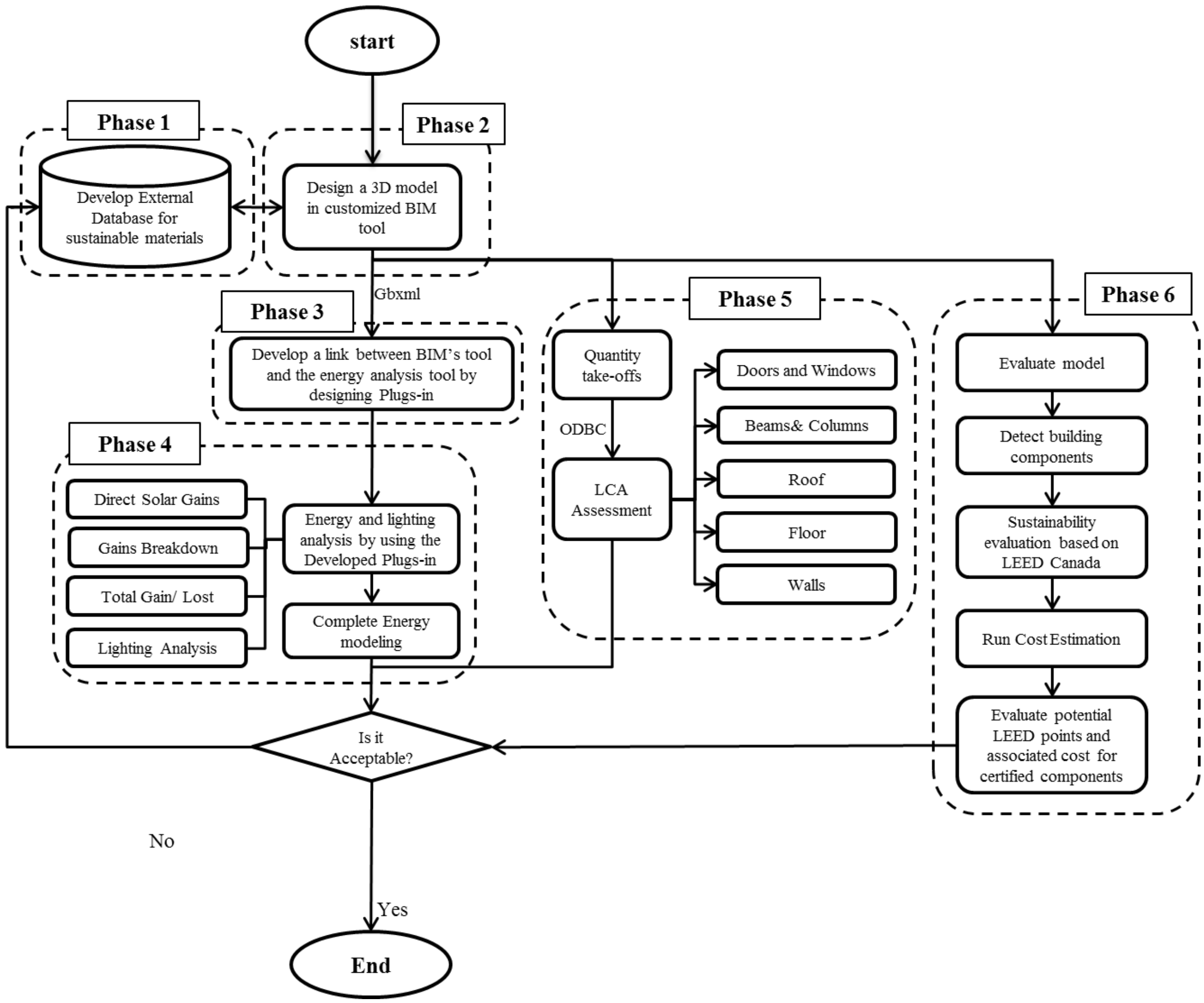

Figure 6. 2. Flowchart of the integration Process

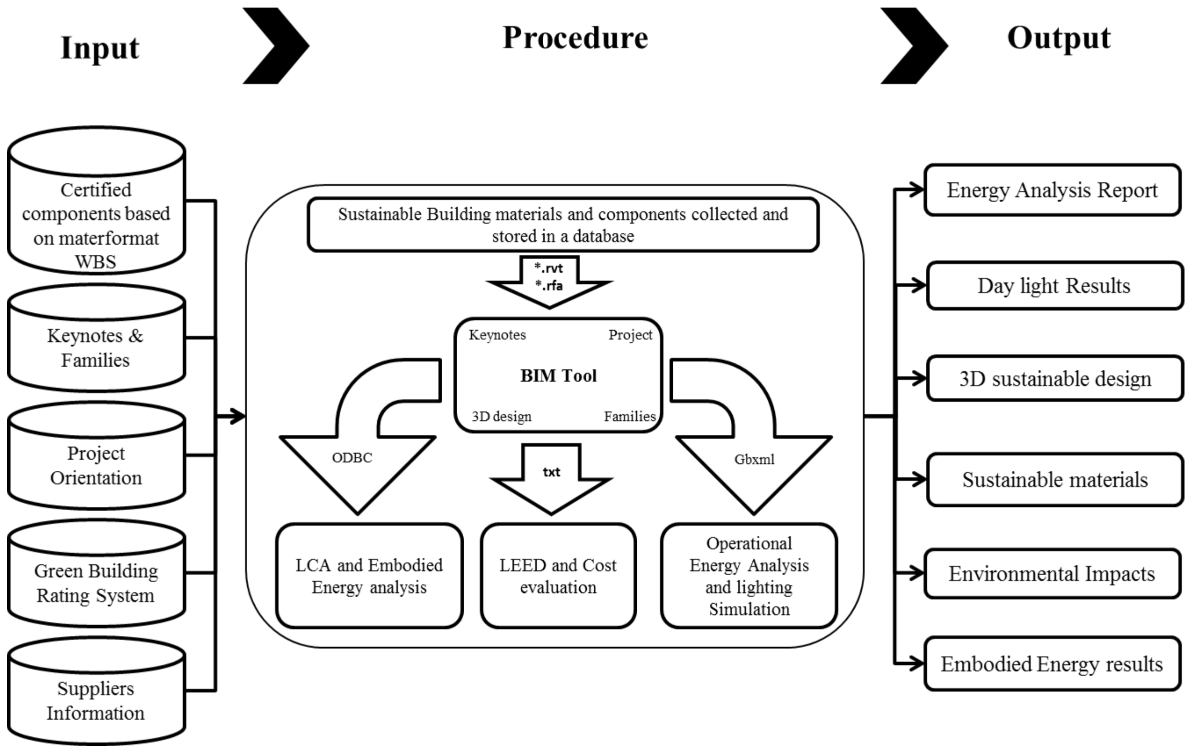

Figure 6. 3. Model's Architecture

To validate this model, its performance is examined through the use of an actual three floor office building project with a conference hall at the fourth floor that is under design process in the city of Montreal. The proposed construction site has a total area of 41,980 ft2, the building's gross area is 16,862 ft2 and it has a perimeter of 1145 ft. The authors created a 3D conceptual design of the current project where its associated sustainable components and materials were selected from the developed database. The components used in the design of the case example had their specifications as close as possible to the ones used in the real design. Every component, such as the floor, walls, the roof, and windows has its associated LEED information linked to the families of the BIM tool and they are already defined in the database of Ecoscorecard, which includes the manufacturers' web pages and contact information. The authors created a conceptual design of the current project where its associated sustainable components and materials were selected from the developed database. The components used in creating the design of the case building had their specifications very close to the ones used in the real design. Every component, such as floor, walls, roof, and windows has its associated LEED information linked to the families inherited in BIM tool and are already defined in the database of the sustainability evaluator tool (Ecoscorecard), which includes the manufacturers' web pages and contact information. The developed model will be used to analyze and simulate the energy and lighting of the project's 3D design and to evaluate its sustainability by calculating the accumulated LEED points that can potentially be earned during the conceptual design stage. Figure 6.4 shows a rendered snapshot of the proposed sustainable office building, which was created using the developed model previously described. This process is implemented in four steps, wherein the model's capabilities and performance are measured using the inherited modules.

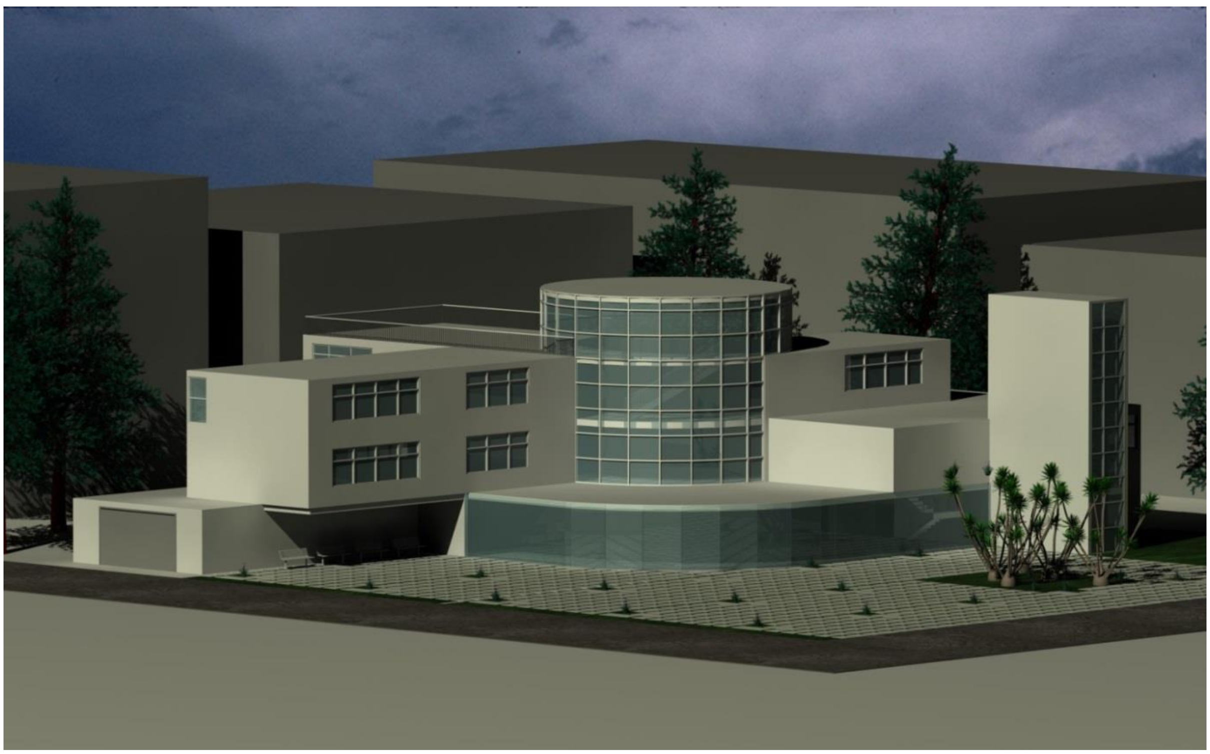

Figure 6. 4. Snapshot of the sustainable case building model

6.5.1. Sustainable Conceptual Design in BIM tool (Step 1)

BIM tool (Autodesk Revit Architecture©) is applied to do the sustainable 3D conceptual design of the case building by using green families and their related keynotes stored in the external database. Once these families' keynote file is linked to the building model, users will select the most appropriate type of certified materials and components for their design. As explained in phase 1, the external database contains detailed information about the suppliers of the green materials used in every family. More than 80% of the components and families used in the case building had their LEED certification points supplied by their manufacturers and stored in the developed external database.

6.5.2. Energy analysis and day lighting simulation (Step 2)

In order to have an accurate energy analysis of the case building, its created 3D geometric model should be converted into an analytical model. First, we have to convert all the spaces into rooms. In BIM tool, rooms are considered to be the equivalent of zones that need to be defined. A thermal zone is a completely enclosed space bounded by its floors, walls and roof and is the basic unit for which the heat loads are calculated. The extent of a “room” is defined by its bounding elements such as walls, floors and roofs. Once a “room” is defined for the purpose of analysing the building’s energy, these bounding elements are converted to 2D surfaces representing their actual geometry. However, overhangs and balconies, which do not have a room, are considered as shading surfaces. In order to determine whether a room is an interior or an exterior it is important to define it’s adjacent in the analytical model. By using the developed plug-in that is loaded in the BIM tool, designers will directly transfer the created 3D model of the building to the energy simulation and analysis tool (Ecotect©) using gbXML format. Moreover, by using the IES-VE plug-ins, which is added to the BIM tool, transferring the 3D BIM model into IES-VE is conceivable based on gbXML format as shown in figure 6.5.

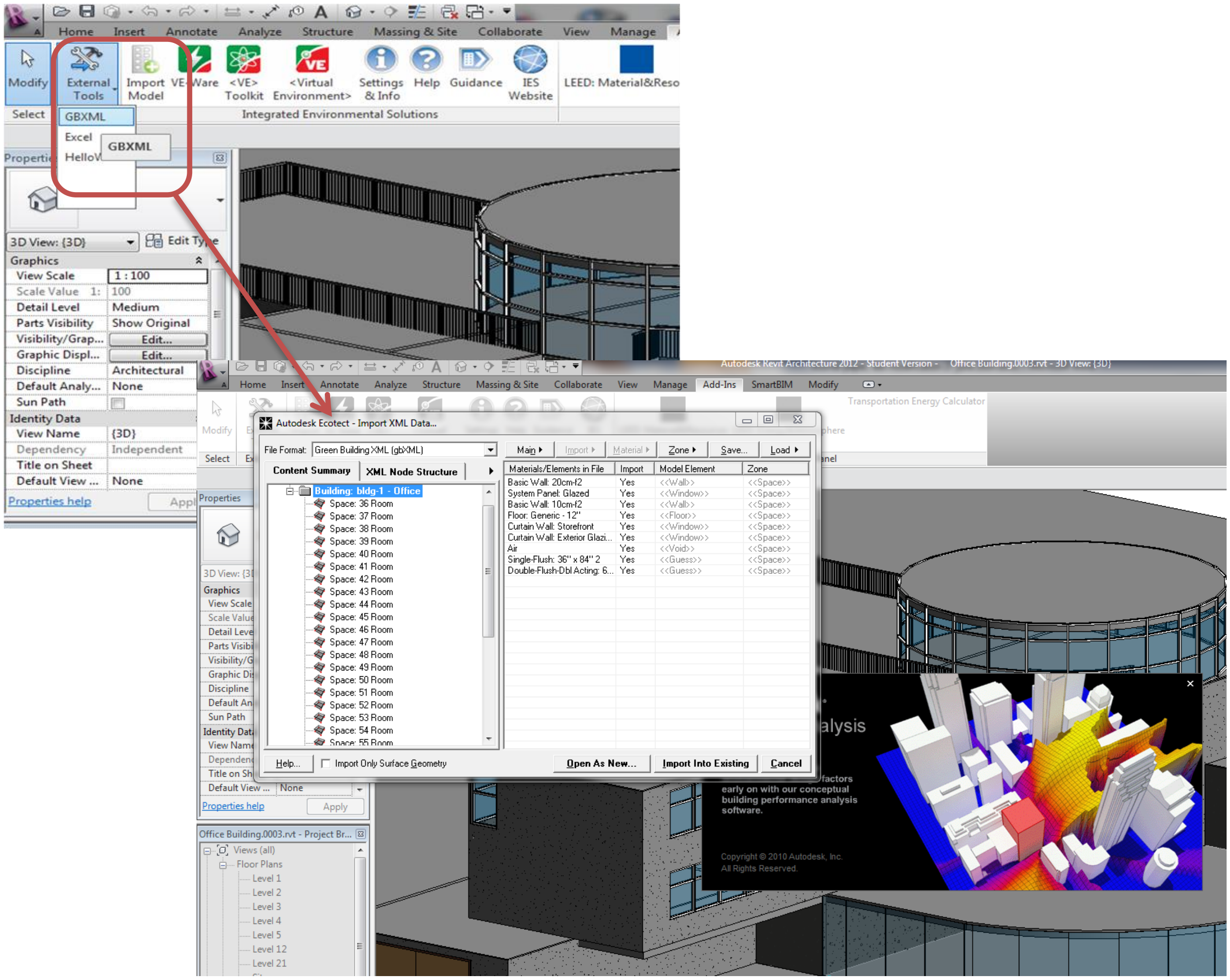

Figure 6. 5. Snapshot of directly transferring BIM model to Ecotect via Plug-in based on gbXML file format

After running the Thermal and Day lighting analysis in Ecotect, it is possible that comprehensive building information other than the geometric one will be transported. In order to test what type of data was included during the integration, a comparison analysis of this data is executed. The building model is tested for building material, thickness, geometry (area and volume), building services, location and building types. All the input variables are kept constant in the base case while the testing is done with one alteration at a time. What BIM brought to energy simulation is an integrative interface that provided the designers a more reliable and consistent building information model for analysis, leading to more accurate simulation results. The biggest advantage of parametric modeling rests in its capacity of updating building information simultaneously with the changes made to the model configuration. In the conceptual design stage, architects and designers could test different design alternatives to find the optimal solution.

As mentioned earlier, gbXML is developed based on XML, which captures data information representation but not the relationships among them. All the geometry information imported from the BIM tool is represented by the “Campus” element. The global child element “Surface” represent all the surfaces in the geometry. There are several attributes defined in a “Surface” such as “id” and “surfaceType”. Every “Surface” element has two representations of geometry, “PlanarGeometry” and “RectangularGeometry”. They both carry the same geometry information. The purpose of this is to double-check whether the translation of geometry from BIM tool is correct or not. Every “RectangularGeometry” has four “CartesianPoint” elements, which represent a surface. Every “CartesianPoint” is represented by a three dimensional coordinate (x,y,z).

There are only five levels to transverse and to get all the coordinates of an “Exterior Wall” location. It is also easy to add other surfaces. In addition, every polyloop, which contains a list of coordinates that makes up a polygon in three-dimensional space, follows a right-hand rule defining the outward normal of a surface. However, gbXML has the ability to carry building environmental sensing information. In terms of geometry, gbXML only acceptes rectangular shape, which is enough for energy simulation.

GbXML file is able to transfer the geometric information such as shape, areas and volumes. However, it is further able to transmit information about location, and construction assignments. It can be seen that the gbXML file is also able to transfer other information such as building type (single family) and building services (VAV single duct). Thus, in order to validate the information that is not transmitted, the gbXML file is modified so that it can recognize the information related to the location, building services and construction assignments while executing the transferring process.

In order to discern that the information related to the selected material used in the model has been completely transmitted over to the energy simulation and analysis tools, a new material is assigned to the 3D model of the case building. The wall’s material is changed to a timber frame wall that consists of brickwork (outer leaf), cavity, plywood (lightweight), mineral fiber slab, and cavity and gypsum plasterboard. However, the option selected in the IES interface for the construction assignments (exterior wall) is kept unchanged.

A quick scan to the IES's results shows that the result is kept unaltered. This means that the newly assigned material in the model does not have any type of effect on the results. To clarify this result, in another case, the timber frame wall was modeled as the wall material, and the same option was selected in the IES interface, which is a timber frame wall. The difference in the results indicates that the selection in the Revit-IES interface overrides any selection made during modeling of the building in Revit. This is important because this indicates a gap in the information transfer in the building model in Revit and analytical model in IES-VE.

Figure 6.6 shows sample results of the day lighting analysis that users can get out of both the Ecotect and IES-VE tools and Figure 6.7 shows sample of the thermal analysis results generated by these tools. In figure 6.6, day lighting simulation provides a visualization measurement of the day light that is gained by every single surface inside the building's model as well as the building's exterior wall surfaces, which is supplied as a percentage of the solar light each surface can get. For example, at the second floor, the maximum percentage of solar gains is for central areas surrounded by glazed curtain walls with 72% while the minimum percentage is 12%, which corresponds to corner areas located far from openings. IES-VE provides solar analysis with 3D visualization showing the amount of light that varies between 386.3 kwh/m² and 1263.47 kwh/m² for the whole building.

In Figure 6.7, a diagram of total gains is based on outside temperature ranging from -26 ˚C to 32.5 ˚C for the City of Montreal for all visible thermal zones. The maximum heat loss corresponding to -26 ˚C temperature is -166 wh/m² and the maximum gain is 54 wh/m² correspond to 32 ˚C. The part of the diagram with condensed points is for the temperature between 0 ˚C to 26 ˚C, which gives an average of -45 wh/m² loss of energy and 10 wh/m² energy gains respectively. Gains breakdown results show the percentage of overall gains/losses for all visible thermal zones through different colors for Conduction, Solar-Air, Direct Solar, Ventilation, Internal and Inter-zonal for a whole year from January 1st – December 31st. As illustrated, conduction has a maximum overall loss with 69.4% (around 840 wh/m²) and direct solar has tremendous gains with 51.7% of energy gains (around 420 wh/m²). IES-VE also gives a total annual energy analysis, total electricity and total net gas manifesting the total system energy based on power (Kw) for the whole year. The analysis shows that the maximum energy consumption of the building is between Jan-Dec with an average of 250 (KW) for the whole system.

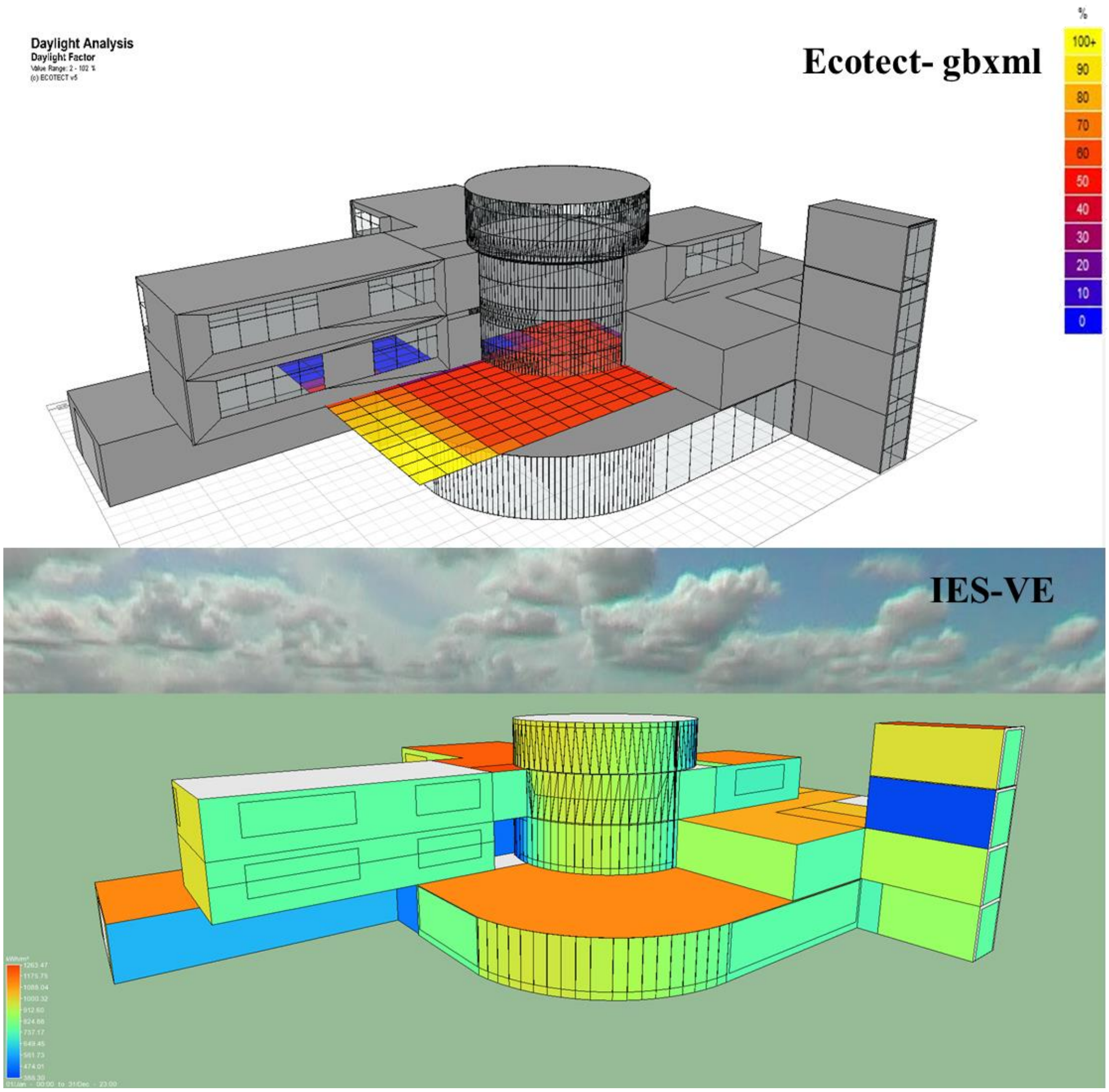

Figure 6. 6. Snapshot of the sample day lighting simulation in Ecotect and IES-VE

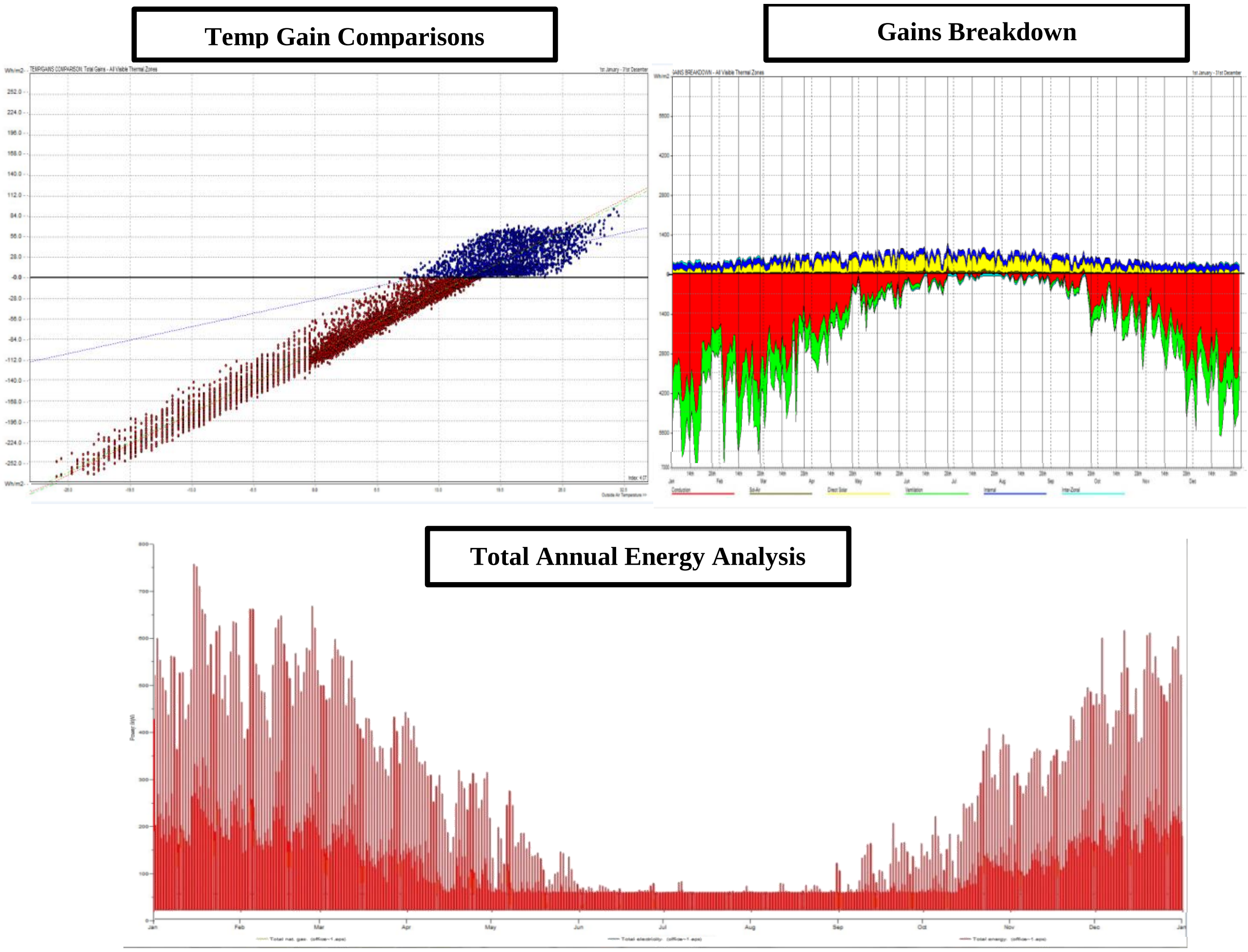

Figure 6. 7. Snapshot of the sample thermal energy analysis in Ecotect

6.5.3. Assessing the LCA and embodied energy analysis results of building components (Step 3)

Once the conceptual design is finished and the energy is analyzed, the building is assessed and analyzed based on the sustainability requirements using the LCA module and its associated tool (ATHENA® Impact Estimator©). This user-friendly tool provides quick results in the form of tables and graphs. The Impact Estimator (IE) allows users to change the design, substitute materials, and make side–by–side comparisons. It also lets users compare similar projects with different floor areas on a unit floor area basis. After that, the IE is able to calculate the primary operating energy including the embodied energy (the energy used to extract, refine and deliver energy) and the related emissions to air, water and land over the life cycle of the building (Athena, 2012). Subsequently, the IE compares the life cycle of the operating and embodied energy and other environmental effects of the proposed building design by allowing users to better understand the inherent trade-offs associated with the increase of the envelope materials (e.g., insulation), which can reduce the operating energy consumption.

First, users input the necessary information such as geographic location, building life and occupancy/type, and, if desired, annual operating energy values into ATHENA. Second, the exported bill of quantities extracted in step 1 is imported as text exchange file into ATHENA® Impact Estimator©. Pre-set dialogue boxes prompt users to describe the different assemblies, such as entering the width, span, and live load of a floor assembly.

While the Impact Estimator offers a wide array of material and assembly combinations, the user needs to enhance the project design with additional materials. It should be noted that when it is decided to add "Extra Basic Materials", the application doesn’t know how or where these materials are to be added and used. Hence, the LCA profile provided for extra basic materials is diminished in the sense that the application delivers the material to the building site, but does not calculate any effects associated with the usage of this material. For instance, using the formerly mentioned case as an example, softwood lumber, which is a green material and is used in different parts of the building, is added beside other assembly groups as extra basic materials.

After entering all the necessary information, Impact Estimator provides series of reports in terms of: 1) Primary Energy Consumption, 2) Acidification Potential 3) Global Warming Potential, 4) Human Health (HH) Respiratory Effects Potential, 5) Ozone Depletion Potential, 6) Photochemical Smog Potential, 7) Eutrophication Potential, 8) Weighted Raw Resource Use, which are the focus of this case example. Figure 8 represents samples of the bar chart reports extracted from ATHENA® Impact Estimator©. As shown in Figure 6.8, foundation, as well as extra basic materials consumes fossil fuel more than other assembly groups (around 3,000,000 MJ). Beams and columns and walls use about 2,500,000 (MJ) of fossil fuel consumption. Conversely, when it comes to Ozone depletion, walls, roofs and foundation with about 0.0014 (Kg CFC) are three groups with noticeable amounts. Rather than extra basic materials, walls, on the other hand, seem to have the most smog potential with around 22000 (Kg No^x) out of the total amount, which is 95,000 (Kg No^x). Foundation creates the highest amount of Global Warming potential, averaging around 320,000 (Kg Co2), followed by the walls, with 240,000

(Kg Co2). Foundation and walls produce similar amount of acidification potential, usually around 85,000 (moles of H+), whereas beams and columns produce much less than the others with around 55,000 (moles of H+). Similarly, the HH Respiratory effects for walls have the most effects, averaging around 2280 out of a total of 6430 (Kg PM2.5). In the ultimate interpretation among the selected components, walls and foundation have the most impact on the environment in comparison with other assembly groups. Two reasons for this can be described here. The former is that walls and foundation are in direct contact with the outdoor environment while having several openings (wants and voids) and the various layers of walls and foundation are not made from sustainable materials based on the information provided by the supplier. The latter reason is that all the green materials stored in the BIM model and its associated library is not supported by ATHENA® Impact Estimator©. The results provided by ATHENA® Impact Estimator© represent an appropriate overview about the EI of the design.

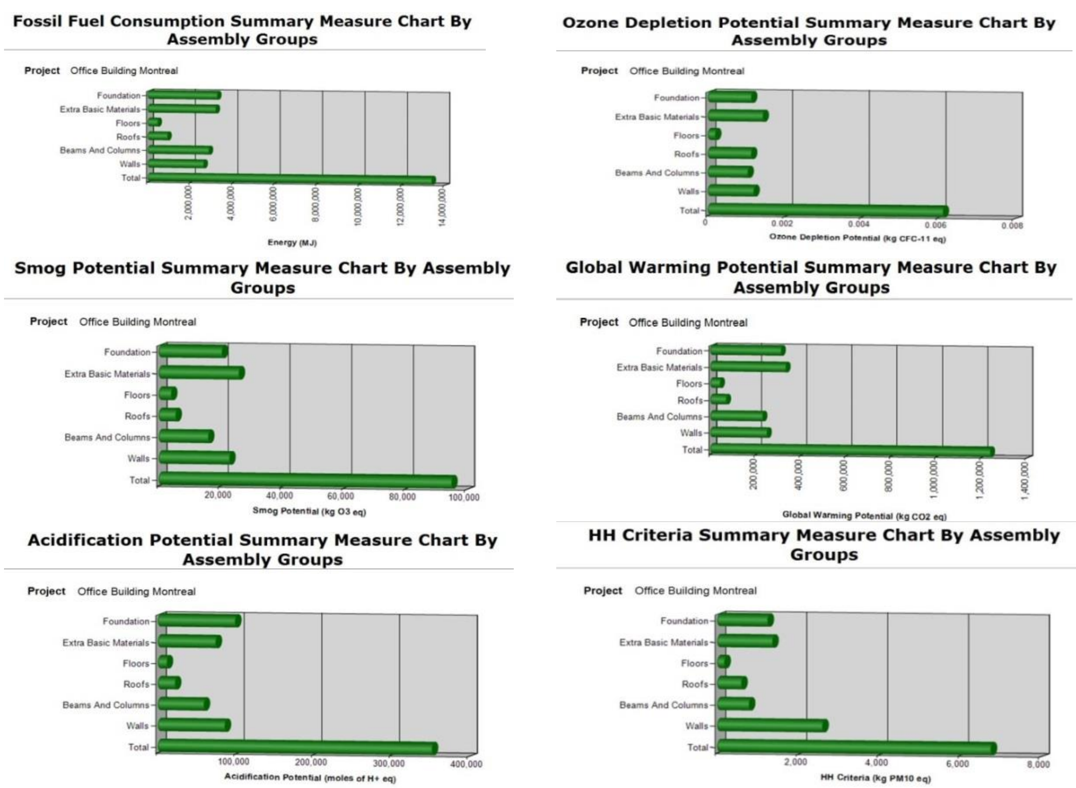

Figure 6. 8. Environmental Impact sample report of the implemented design

The embodied energy of every building's component is calculated and its result is generated and supplied as shown in Figure 6.9. IE takes into account the energy used to construct the structural elements of the building, the emissions to air, water and land associated with the on-site construction activity as well as the energy used to transport the materials and components from the manufacturer to a national distribution centre and from that centre to the building construction site. As illustrated in Figure 6.9, in the case building, it is obvious that the walls' materials have the highest embodied energy consumption with a total of 6,456,764 MJ based on different types of energy description. Beams and columns have the second highest embodied energy consumption (1,855,880 MJ). Furthermore, 20,272,484.27 MJ of the energy consumed in this building is operating fossil fuel energy while 13,413,217 MJ is embodied fossil fuel energy.

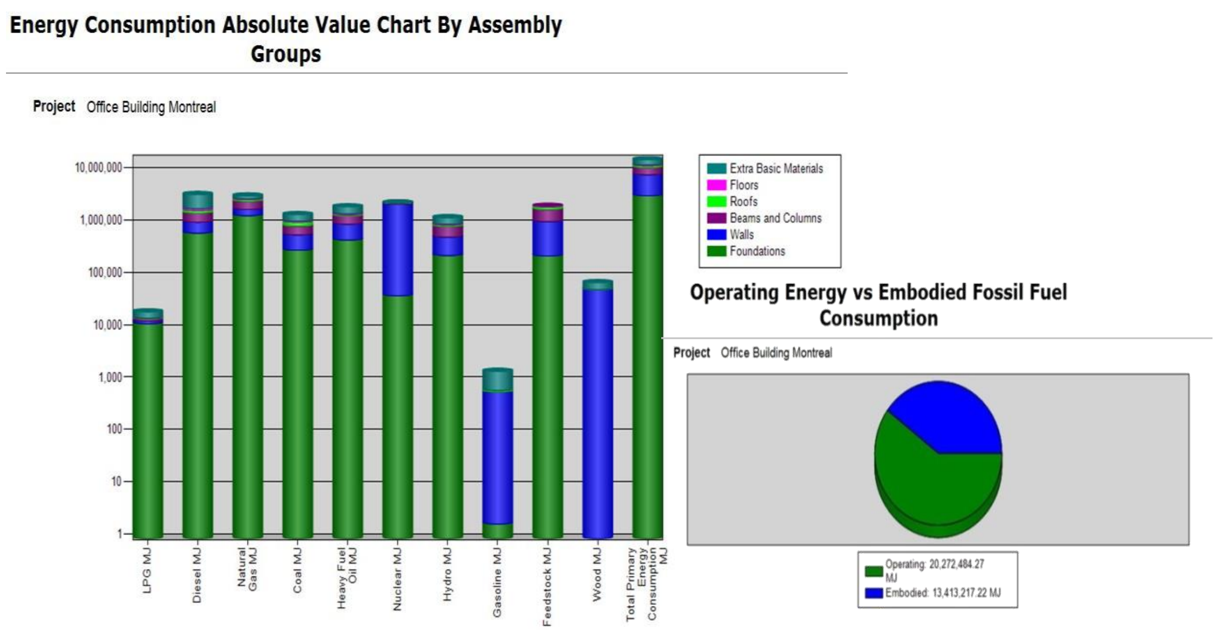

Figure 6. 9. Embodied Energy analysis of each building component in the designed model

To calculate the transportation embodied energy, a plug-in is developed by authors based on the algorithm described in phase 5. The algorithm receives weight of every building component (lb) from user and implements the truck selection procedure. Then, the developed plug-in uses the API of google map to calculate the distance between the location (origin) of the materials' suppliers and the location of the project (destination) once the required postal codes are entered by the user. As illustrated in figure 6.10, when the required data (i.e. Weight of the material, postal codes of origin and destination) is entered, the plug-in calculates the transportation energy of every building component (MJ) as well as the number of trucks and their types. Clicking the total icon in the form all the amounts of transportation energy calculated in each section and represents the total transportation energy which has to be added to the embodied energy calculated by Athena. For example, by considering the materials of the walls' in the case building and by assuming a unit weight of 55 lb. /SF and a calculated total surface area of 16,360 SF for all the walls, the total weight of the wall's material will be around 899,800 lb. Using the developed plug-in (figure 6.10) shows that a combination of one truck of type 2 and thirteen trucks of type 4 is a proper option for transporting the materials. While the fuel consumption for truck 4 and truck 2 are 4.14 MPG and 5.43 MPG respectively, entering the postal code of the origin and destination would lead to an approximate measurement of the distance to be 9.1 miles, thus the consumed embodied energy for transporting the wall's material is calculated to be around 3988.8 MJ. Same processes are applied for the rest of the building components and accordingly the total transportation energy would be calculated to be around 38934.67 MJ, as shown in figure 6.10.

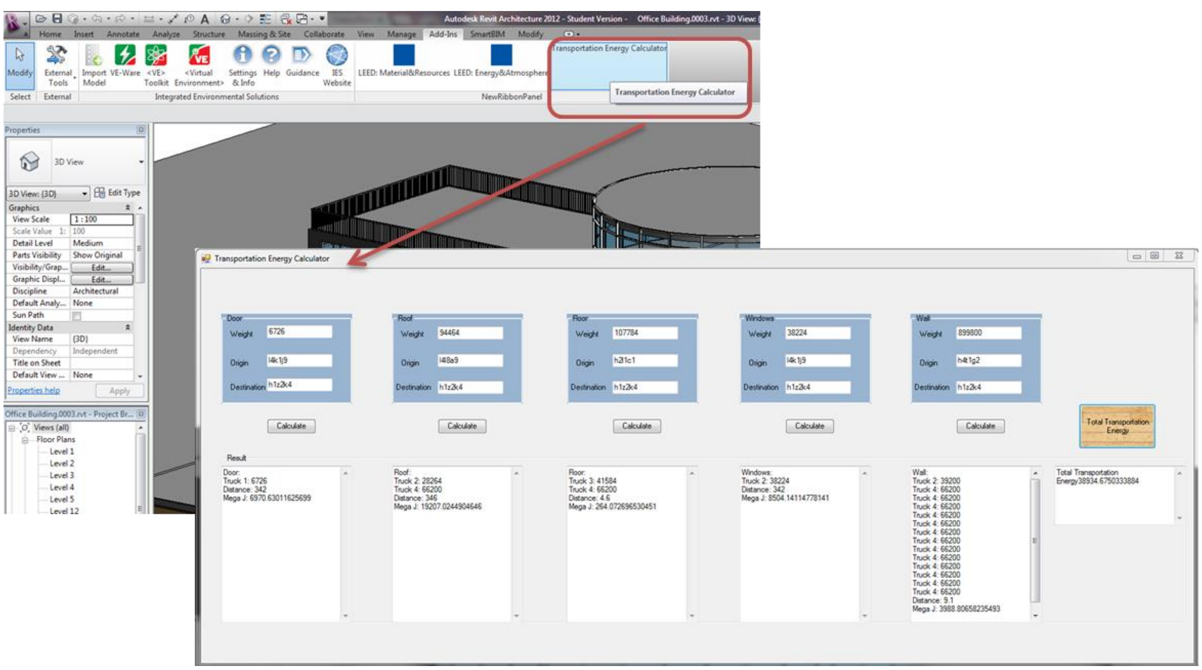

Figure 6. 10. Snapshot of the developed plug-in to calculate the transportation embodied energy for every building component

6.5.4. Environmental Evaluation and calculation of the potential LEED points (step 4)

By running the sustainability evaluator (Ecoscorecard©) plug-in added on in BIM tool, designers are able to do a model evaluation based on different green building rating systems as described in the methodology and development section. The result of the EcoScorecard is shown in Figure 6.11, where 52.9% of the model's components are compiled from sustainable materials and families that are already defined in the Smart BIM database and detected by the EcoScorecard. By selecting the desired green building rating system and clicking the "evaluate model" button, users are able to see the analysis results in detail and save them as a PDF file. In this paper, LEED® Canada New Construction v1.0 is used to evaluate the designed model. In this case, the authors are able to identify the potential points earned by the 3D design based on the information provided by the EcoScorecard.

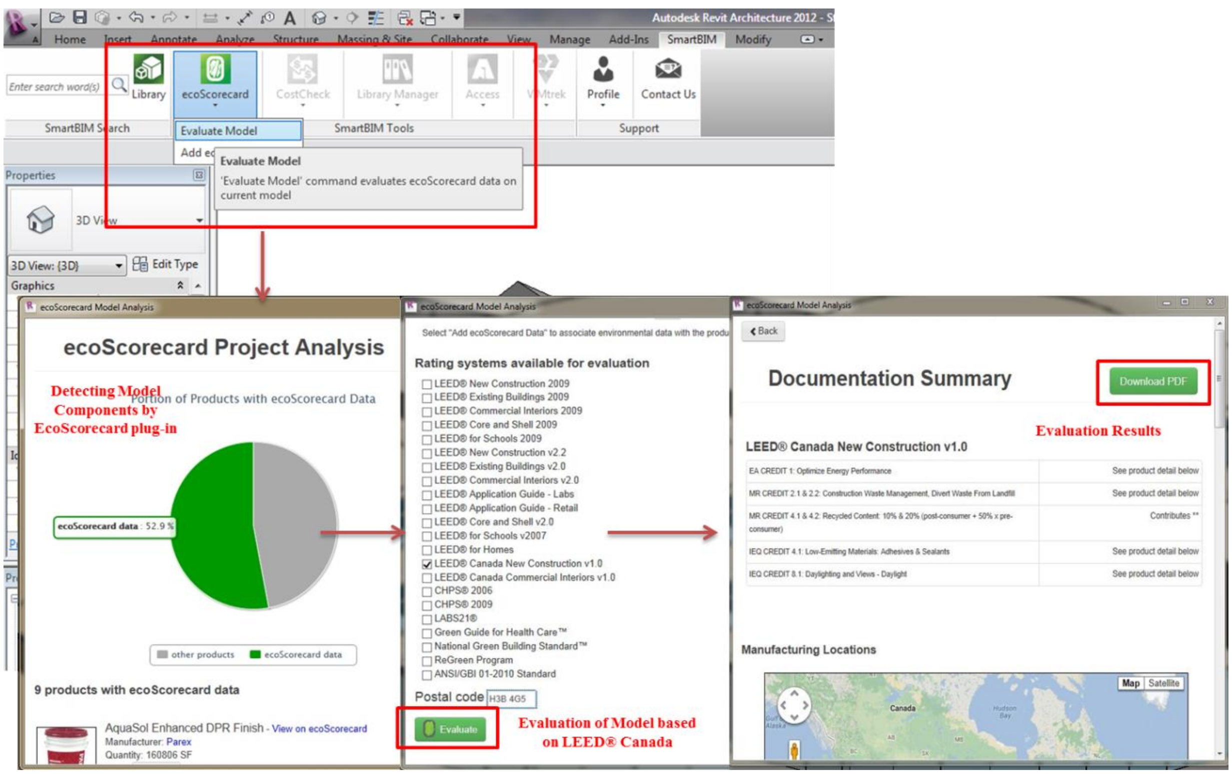

Figure 6. 11. Snapshot of using Ecoscorecard plug-in in Autodesk Revit to detect and evaluate model components based on LEED (CaGBC)

Table 6.3 offers information related to the materials and their associated potential LEED points as well as the actual points earned by the design developed in Step 1 based on the results of the EcoScorecard LEED evaluation. As shown in Table 6.3, the detected components by the plug-in get 44 LEED points are based on the CaGBC rating system. This is an approximated number of the LEED points that are earned by the designed case building since the focus of this study is at the conceptual design stage, which means that the calculated points do not necessarily reflect the final number that can be earned when the building is completed. The intent is to simply provide owners and designers with an idea of how many potential LEED points the proposed building might earn if a decision is made to continue the project. At the conceptual stage, owners and designers do not have detailed information about the project, yet this integration will help them generate an approximated idea that will allow them to realize the potential LEED points the designed 3D model can earn.

Table 6. 3. Potential and actual LEED points that may earned by the model

LEED-NC Credits that can be earned by each family and assembly groups using BIM-based performance analysis software			**Roof**		**Floor**		**Windows**		**Doors**		**Wall**	
LEED Credit	**Credit Description**	**LEED Points**	PEP	EPM	PEP	EPM	PEP	EPM	PEP	EPM	PEP	EPM
Sustainable Sites												
SSp1	Construction Activity Pollution Prevention	Required										
SSc1	Site Selection	1										
SSc2	Development Density and Community Connectivity	3,5										
SSc3	Brownfield Redevelopment	1										
SSc4.1	Public Transportation Access	3,6										
SSc4.2	Bicycle Storage and Changing Rooms	1										
SSc4.3	Low-Emitting and Fuel-Efficient Vehicles	3										
SSc4.4	Parking Capacity	2										
SSc5.1	Protect and Restore Habitat	1										
SSc5.2	Maximize Open Space	1										
SSc6.1	Storm water Design: Quantity Control	1										
SSc6.2	Storm water Design: Quality Control	1										
SSc7.1	Heat Island Effect: Non-Roof	1										
SSc7.2	Heat Island Effect: Roof	1										
SSc8	Light Pollution Reduction	1										
Water Efficiency												
WEp1	Water Use Reduction	Required										
WEc1	Water Efficient Landscaping	2,4										
WEc2	Innovative Wastewater Technologies	2										
WEc3	Water Use Reduction	2-4										
Energy & Atmosphere												
EAp1	Fundamental Commissioning of Building Energy Systems	Required										
EAp2	Minimum Energy Performance	Required							*			
EAp3	Fundamental Refrigerant Management	Required										
EAc1	Optimize Energy Performance	1-19	*	6 points			•	8 pts	*	6 points	•	8 pts
EAc2	On-Site Renewable Energy	1-7										
EAc3	Enhanced Commissioning	2										
EAc4	Enhanced Refrigerant Management	2										
EAc5	Measurement and Verification	3										
EAc6	Green Power	2										
Materials & Resources												
MRp1	Storage and Collection of Recyclables	Required										
MRc1.1	Building Reuse: Maintain Existing Walls, Floors, and Roof	1-3										
MRc1.2	Building Reuse: Maintain Interior Non-Structural Elements	1										
MRc2	Construction Waste Management	1-2										
MRc3	Materials Reuse	1-2	*	1 point	*	1point	*	1pt	*	1point		
MRc4	Recycled Content	1-2	*	1 point			*	1pt				
MRc5	Regional Materials	1-2	*	1 point	*	1point	*	1pt	*	1point		
MRc6	Rapidly Renewable Materials	1										
MRc7	Certified Wood	1										
Indoor Environmental Quality												
EQp1	Minimum Indoor Air Quality (IAQ) Performance	Required										
EQp2	Environmental Tobacco Smoke (ETS) Control	Required										
EQc1	Outdoor Air Delivery Monitoring	1										
EQc2	Increased Ventilation	1										
EQc3.1	Construction IAQ Management Plan: During Construction	1										
EQc3.2	Construction IAQ Management Plan: Before Occupancy	1										
EQc4.1	Low-Emitting Materials: Adhesives and Sealants	1					*	1point				
EQc4.2	Low-Emitting Materials: Paints and Coatings	1										
EQc4.3	Low-Emitting Materials: Flooring Systems	1			*	1point						
EQc4.4	Low-Emitting Materials: Composite Wood and Agrifiber products	1										
EQc5	Indoor Chemical and Pollutant Source Control	1										
EQc6.1	Controllability of System: Lighting	1										
EQc6.2	Controllability of System: Thermal Comfort	1										
EQc7.1	Thermal Comfort: Design	1										
EQc7.2	Thermal Comfort: Verification	1										
EQc8.1	Daylight and Views: Daylight	1	*	1 point			*	1point	*	1point	*	1point
EQc8.2	Daylight and Views: Views	1										
Innovation & Design Process												
IDc1	Innovation in Design	1-5										
IDc2	Accredited Professional	1										
Regional Priority												
RPc1	Durable Building	1										
RPc2	Regional Priority Credit	1-3										

Since not all suppliers provide the cost of products on their website, authors used RS-Means cost data to prepare preliminary cost estimate for the case building and store it in that specific family in BIM tool as shown in Figure 6.12. Table 4 illustrates the total estimated cost of each building component which is calculated using R.S. Means Green Building Cost database. In this database the unit cost of each family is calculated based on the year 2013 national average value and adjusted for the city of Montreal. To prepare the cost estimate, materials with specifications similar to the quantity take off extracted from the developed 3D design are selected from R.S. Means database. However, as illustrated in Table 6.4, the preliminary cost estimate of the building components using the proposed method is calculated to be $1,131,303.43 while the actual estimated cost was calculated to be $ 1,045,753 for year 2013 that reflects a 7% difference in the values, which is acceptable for the conceptual stage where little information about the project is known.

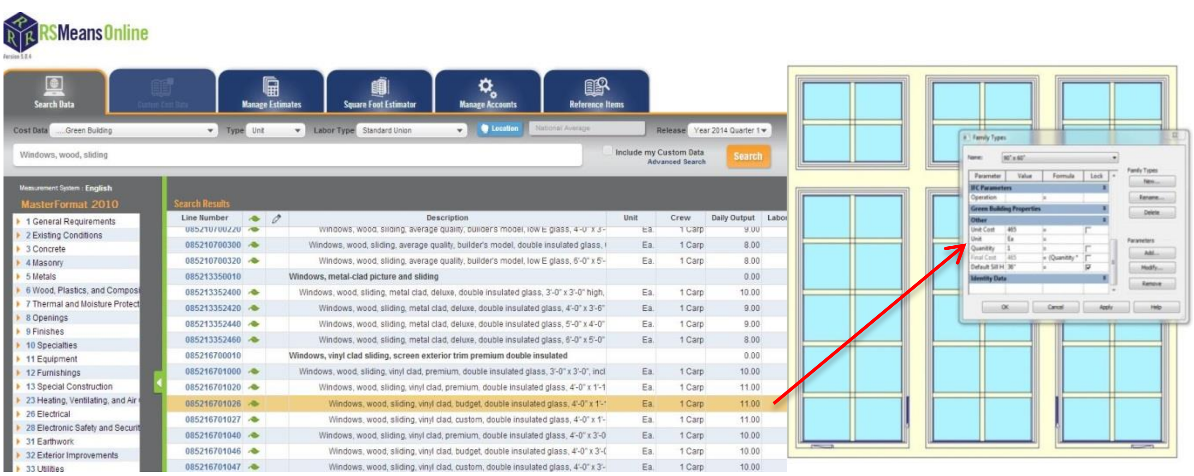

Figure 6. 12. Snapshot of storing the unit cost of sustainable window family using RS-Means cost database

Table 6. 4. Associated cost of the selected components based on R.S. Means cost data

Description (Green Building)	Unit	Quantity	Total Unit Cost ($)	Total Item Cost ($)	Description (Typical Building)	Total Unit Cost ($)	Total Item actual Cost ($)
Windows							
Insulating glass, 2 lites, clear, 3/16" float, for 5/8" thick unit, 15-30 SF	S.F.	2681	$16.89	$ 45,282.09	Windows, aluminum, awning, insulated glass, 4'-5" x 5'-3"	$58.64/ SF	$157,214
Frames, steel, knock down, "B" label, single, hollow metal, 14 ga., up to 5-3/4" deep, 7'-0" h x 4'-0" w	Ea.	238	$ 232.13	$55,246.94			
Roof							
Structural insulated panels, 7/16" OSB both sides, straw core, 4-38" thick, roofs, including splines	S.F.	6560	$12.53	$82,196.80	Roof, concrete, slab form, open web bar joist @ 2' OC, on W beam and wall, 25'x25' bay, 26" deep, 75 PSF superimposed	$14.91	$97,809
Insulating roof fill, with expanded volcanic glass rock, 3" thick	S.F.	6560	$2.44	$16,006.40			
Floor							
Resilient Flooring, cork tile, standard finish, 5/16" thick	S.F.	14,970	$12.43	$186,077.1	Floor, concrete, slab form, open web bar joist @ 2' OC, on W beam and wall, 25'x25' bay, 26" deep, 75 PSF superimposed	$14.91	$223,203
Doors							
Doors, glass, sliding, vinyl clad, 6'-0" x 6'-8" high, insulated glass	Opng	3	$1,540.32	$4,620.96	Door, aluminum & glass, with transom, narrow stile, double door, hardware, 6'-0" x 10'-0" opening	$7.72/ ft^2	$9,787
Doors, wood, paneled, interior, five panel, solid, fir, 3'-0" x 6'-8" x 1-3/8" thick	Ea.	18	$431.42	$7,765.56			
Walls							
Precast wall panel, smooth, gray, un-insulated, high rise, 4' x 8' x 4" thick, 3000 psi	S.F.	16360	$37.62	$615,463.2	Brick walls,13.5 brick per square foot, 8" thick wall, includes mortar, 8% brick waste and 25% mortar waste, vertical reinforcement and grout, excludes scaffolding & horizontal joint reinforcement	$29.97	$490,309
Railing & Stairs							
Stair, shop fabricated, steel, 3'-6" W, including picket railing, stringers, metal pan treads, excl concrete for pan treads, per riser	Riser	96	$519.83	$49,903.68	Stairs, steel, cement filled metal pan & picket rail, 16 risers, with landing	$5.27/ ft^2	$67,431.4
Railing, pipe, steel, primed, 3 rails, 3'-6" high, posts @ 5' O.C., 1-1/4" diameter, shop fabricated	L.F.	132	$45.36	$20,548.08			
Approximated Construction Cost	**$1,131,303.43**			**Actual approximated cost**		**$ 1,045,753**	

6.7. Conclusion

The novelty highlighted in this paper describes the model's different modules, which are integrated into each other based on an automated process by creating new plug-ins and improving the functionality of the existing ones so that users will be able to start the sustainable design of a proposed building project at the conceptual stage of its life cycle in a timely and cost effective. Using a BIM integrated platform moves the design decisions forward at the early stage especially when comparing different design alternatives, which is considered as an attribute of this research.

The developed model enables users compare and select different materials and components, which are stored in the external database, to be used in their design based on the energy and sustainability specifications and cost. This accelerates the process of modifying building components early at the conceptual design stage in case the selected ones do not meet owners or designers requirements. Missing information during the transformation process from BIM tool to the other ones (i.e., energy analysis and simulation) include the information required as input by different software. Some information needs to be entered manually by the user after the transferring process, while other type of information is automatically assumed by the software itself (i.e. information about the type of materials when transferring it from Revit to Ecotect or IES-VE). The developed database was designed based on the collected information that contained limited numbers of certified components, all of which are designed and provided by the manufacturing companies. This is a limitation for the model because it does not cover all the existing green elements and, as was previously mentioned, only 52.9% of those materials and components were detected and defined in the Ecoscorecard database. This means that there are several green families that need to be designed, converted to BIM format files and added to the database.

In this research, different energy tools have been used and their results are compared. While Ecotect gives annual thermal consumption and peak loads for worst-case times, the IES Apache Simulator gives comprehensive information about the total annual energy consumption and room loads. The variation in Ecotect in terms of the heating and cooling loads is due to the calculation method used by this tool. Ecotect uses the worst design annual load case while the ASHRAE load calculator built into IES uses the worst monthly scenario (January) for heating loads and five months long (May-September) scenario for cooling loads. The discrepancy in the results between Revit, IES and Ecotect was expected to occur because of the different load calculation techniques, calculation engines and variation in the materials types and their associated values found in these tools.

The results generated by the different modules are evaluated based on diverse economical perspective. Energy analysis results are good feedback to the design team about the potential energy that can be gained or lost within a year by the proposed building. Using these data can ease the way of estimating the energy cost which is a major part of the operation cost for any building. LCA is in direct relation with Life Cycle Cost through different attributes such as process-related costs, Environmental Insurance, impact on sales volume of the building components, Labelling costs, future taxes or abatement costs and etc. Along with the obvious environmental advantages, LEED-certified buildings cost less to operate and are more desirable for commercial and residential occupants. As it is an ongoing research, part of the future work is related to enhance the external BIM database as well as developing a plug-in containing LEED points and requirements to efficiently calculate and quantify sustainability of the building components.

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CHAPTER 7

TECHNICAL PAPER IV

Integrating Building Information Modeling (BIM) and LEED System at the Conceptual Design Stage of Sustainable Buildings

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(Submitted in Journal of Sustainable Cities and Society, Date of Submission: 31/ 03/ 2015)

Abstract- Designing environmentally-friendly buildings that provide both high performance and cost savings is of increasing interest in the development of sustainable cities. Today, we are looking at not just buildings' certification but sustainable practices that go beyond ratings to satisfy our social responsibilities. The construction industry in general will benefit from an integrated tool that will help optimize the selection process of materials, equipments, and systems at every stage of a proposed building's life. Building Information Modeling (BIM) has the potential to aid designers to select the right type of materials during the early design stage and to make vital decisions that have a great impact on the life cycle of sustainable buildings.

This paper describes a methodology that integrates BIM with the Canadian green building certification system (LEED©), and it explains how this integration would assist project teams in making sustainability related decisions while accumulating the required number of points with regard to the applied green building rating system. The methodology depicts the implementation of a model that automatically calculates the compiled number of LEED certification points and related registration costs for green and certified materials used in designing sustainable buildings all within the application of BIM concept. Using BIM in this methodology will help designers to invent and animate sustainable buildings in 3D mode easily and efficiently at the conceptual stage. The design information of the proposed sustainable building will be produced in a timely manner by using new plug-ins, which is developed for that reason, and which will link the BIM model with an external database that stores sustainable materials and assembly groups. A real case project is presented to illustrate the usefulness and capabilities of the proposed model.

7.1. Introduction

Studies indicate that the demand for sustainable buildings that have minimal environmental impacts on society is slowly increasing (Biswas et al, 2008). Therefore, the construction industry needs to adopt new ways for designing buildings in order to reduce pressure on the environment such as sustainability approach. Incorporating sustainability principles at the conceptual stage is attained by using sustainable design in which designers need to identify associated materials and components based on the selected green building certification system.

Lately, the Architecture, Engineering and Construction (AEC) industry has witnessed an increasing interest in using Building Information Modeling (BIM) in conjunction with sustainability principles in the design and construction of green building projects. BIM tools have the ability to help designers explore different design alternatives at the early stage and to automatically transfer the necessary information to energy analysis and simulation tools in an efficient and error free manner. On the other hand, by using BIM tools owners can better visualize the development of their building projects over the different stages of their life. The building team uses BIM models to coordinate activities, takeoff material quantities, and detect possible clashes between equipment and spaces (Barnes et al., 2009).

Leadership in Energy and Environmental Design (LEED), which is a recognized rating system for buildings and homes (USGBC, 2011), has become a thriving business paradigm in promoting sustainability in the AEC industry due to governmental endorsement and the strong marketing of the USA Green Building Council (USGBC) and the Canada Green Building Council (CaGBC). LEED outlines five key areas which are 1) sustainable sites; 2) water efficiency; 3) energy and atmosphere; 4) material selection; and 5) indoor environmental quality. LEED has become such an important aspect of green building that some federal agencies and local governments are requiring their new and existing buildings to be at least LEED-certified. A number of professionals, from architects to construction managers in 41 different countries, are using this rating system. There are different types of systems under LEED that can be applied for homes, interiors, core and shell, and neighborhood development, however the focus of this paper is on LEED Canada for New Construction (NC). LEED-NC addresses the whole building and building site, which cover the design and construction process of new buildings and major renovations of existing ones. LEED–NC is used also for building upgrades, under the condition that less than 50 percent of the building occupants remain in the building during the upgrading process.

According to Eastman et al. (2008), developing a parametric modeling within BIM is capable of capturing project information and generating documentation. With special care taken on the software side, an enhanced BIM application could potentially resolve what used to be obstinate problems in sustainable design delivery (i.e. dealing with the complexity of conducting full building energy simulation, acoustical analysis, and day lighting design). The possibility that the design team can automatically access the green building rating system points and associated registration and certification cost has not yet been considered into one simple model. The advantage of using BIM is its ability to act as a single source of all project information that the design team needs to analyze and modify the building before its physical implementation. The LEED rating system is a consistent measure of how a building impacts the environment. A major aspect of LEED is the documentation and calculations that must be submitted in order to reach the required type of certification. As more advances are made to BIM tool, more possibilities of analyzing the building orientation, geometry, and carbon footprint are available. BIM tools' features such as materials takeoff, element property parameters, and material library can help in determining the LEED credits that a building may acieve.

This research describes a methodology to implement an automated and integrated platform to do sustainable design for proposed buildings at their conceptual stage. The methodology is implemented through the design and development of a model that simplifies the process of designing sustainable buildings and transferring the design information to list the potential certification points that can be earned based on the Canadian LEED Certification system. The methodology incorporates an integrated model capable of guiding users when performing sustainable design for new building projects. The integrated model uses the LEED information of building components, which are stored in the external database that is, by its turn, connected to BIM tool to calculate the sum of LEED points for New Construction. The major task of the model is to collect lists of green products and certified materials and have them linked to the database of BIM tool. Creating and linking such a database to BIM tool helps users design and animate sustainable buildings easily and efficiently at the conceptual stage. Part of this integrated methodology is to develop new plug-ins to be inherited into BIM tool in order to aid users connect their design models with the sustainability evaluator in an efficient and consistent manner. Automating the process of identifying the potential number of points that the new sustainable building must accumulate to comply with the desired level of certification and estimating the cost of certification will minimize user input and increase the calculations efficiency.

7.2. Literature Review

The main objective of sustainable design is to create built environments that are livable, comfortable and safe. Sustainable design requires reducing the depletion of critical resources (i.e. energy, water, and raw materials) as well as preventing environmental degradation caused by infrastructure and facilities throughout their life cycle. A unique challenge the AEC industry is facing in relation to the sustainability principles is to meet the demand for new and renovated facilities that are accessible, secure and healthy while minimizing their impact on the society, the economy and the environment. The Whole Building Design Guide (WBDG, 2012) represents the following five fundamental principles for sustainable design: 1) Optimize site design including locations of access roads, parking, vehicle barriers, and perimeter lighting; and improve energy performance by reducing the dependence on fossil fuel-derived energy; 2) Use water efficiently and reuse or recycle water for on-site use; 3) Use materials with minimal life-cycle environmental impacts on such things as global warming, resource depletion, and human toxicity; 4) Enhance Indoor Environmental Quality (IEQ) which means maximize day lighting and have appropriate ventilation and moisture control; 5) Optimize acoustic performance; and 6) avoid the use of materials with high Volatile Organic Compound (VOC) emissions. Furthermore, considering the operating and maintenance issues during the conceptual design stage of a building project will contribute to enhancing the inhabitants' productivity, reducing energy costs, and improving the working environment.

Green building certification system can be used as a design and operation guidance, to document progress toward a design or operational performance target, to compare buildings by using the certification systems structure, and to record the design and operation outcomes and/or strategies used in the building (N. Wang et al., 2012).

As the context varies, rating systems in different countries tend to give priority to certain sustainability indicators but the general scope is quite consistent. These indicators embedded in current major green building rating systems address related issues such as land degradation, biodiversity, water shortage, energy efficiency, renewable energy, carbon emission, air pollution, materials and resources, and indoor environmental quality.

Several methodologies have been developed to establish the degree of accomplishment of environmental goals, and to guide the planning and design processes. For instance, Building Research Establishment Environmental Assessment Method (BREEAM) (Baldwin R et al., 1998), Green Star from Australia (GBCA, 2008), the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) from Japan (CASBEE, 2008), the Building and Environmental Performance Assessment Criteria (BEPAC) from Canada (R.J. Cole, 1993), and the Leadership in Energy and Environmental Design (LEED) from the United States (USGBC, 2011) are developed and are currently widely applied. Very comprehensive inventories of the available tools for environmental assessment methods can be found (G.K.C. Ding, 2008) such as the whole Building Design Guide (WBDG, 2012) and the World Green Building Council (WGBC, 2008).

Although the existing methods and tools have an extended use, LEED has established strong credibility among the experts (Pulselli et al., 2007). The LEED system comprised 7500 company and organization members, validating its importance as the standard environmental performance measure of buildings and becoming a reference system for the design, construction, and operation of green buildings beyond the U.S. (Bowyer, 2007).

LEED encompasses a collection of sustainability indicators to holistically evaluate the building performance and to identify how green the building is. The selection of these indicators does not need specialized knowledge since the issues confronting the industry are straightforward and well understood by the professional community, and to a certain extent, by the general public.

The USGBC introduced the first LEED green building rating system in 1998 as LEED for New Construction (LEED-NC). Then new systems were introduced and LEED became a portfolio, and kept evolving over time. The current version is LEED v4, which addresses 21 different market sector adaptations, including new and existing data centers, new and existing warehouse and distribution centers, hospitality, existing schools, existing retail, and multifamily midrise residents (LEED, 2013). While, LEED 2009 version included New Construction, Core and Shell, Commercial Interior, Schools, etc. LEED v3 is a web-based version of LEED that project teams use to manage the LEED registration and certification processes; and the Certification Model (an expanded certification infrastructure based on ISO standards, administered by the Green Building Certification Institute (GBCI) for improved capacity, speed and performance).

Generally, LEED provides a single score that measures the building's rating or assessment, according to the cumulative points in different impact categories, which are then summed to attain the total score. To attain LEED certification, a project must first comply with LEED prerequisite items. Then there is a range of credits that projects can attain to qualify for different LEED certification levels: certified, silver, gold, and platinum, by meeting increasing minimum point levels (Kibert, 2005). LEED Canada-NC 1.0 (NC standard for new construction and major renovations) is the Canadian version of the LEED scoring system. It is approved by the USGBC and was released by the CaGBC in December 2004. An addendum to LEED Canada-NC 1.0 that was developed in 2007 reflects clarifications and improved the requirements introduced by the USGBC for LEED-NC 2.2, along with few other improvements that include the durable building credit. CaGBC is the source for LEED Canada updates and reference information, including templates.

As an example, in LEED Canada for newly constructed buildings, the point range for each level varies: from 26 to 32 points (certified), from 33 to 38 points (silver), from 39 to 51 points (gold) and from 52 to 70 points (platinum). LEED certification addresses specific environmental impacts related to buildings, utilizing a whole-building environmental performance and assessment approach. The main categories of criteria include sustainable site (SS), water efficiency (WE), energy and atmosphere (EA), materials and resources (MR), indoor air quality (IQ), and the innovation and design process (ID). Each category contains a number of criteria and sub-criteria, some of which are assigned a certain number of credits and others are considered as prerequisites (CaGBC, 2011).

A study conducted by Wedding (2007) summarizes the benefits and growth of LEED certified buildings and highlights evidence of the inconsistency between the expected and actual benefits of LEED certification as well as suggestions for revisions to LEED's Energy & Atmosphere

(EA) section to reduce the variation and magnitude in the energy-related environmental impacts of LEED certified buildings. The results of that study show that variability in impacts from LEED certified buildings could be reduced by 62% and the median magnitude could be reduced by 30%. Mereb (2008) developed a tool called GREENOMETER-7, which is a Life Cycle Assessment (LCA) forecasting tool that assesses the building at the micro- and macro- levels. The micro-assessment level provides in-depth analysis of the building products, components, and operations; while the macro-assessment level measures the sustainability performance of the building as a whole and covers areas that are not applicable at the product or component level. GREENOMETER-7 can be applied to justify LEED scores, for assessing the LEED certification level of a building at the conceptual design stage, and ensures incorporating LCA into the LEED system. The Energy and Atmosphere (EA) and Materials and Resources (MR) criteria represent about half of the total points in the LEED certification system. Energy and Atmosphere, also known as energy conservation and renewal energy, is used to maximize the application of renewable energy and other low-impact energy sources such as wind turbines, which will minimize adverse impacts on the environment. However, traditional energy consumption, such as nuclear and gas turbine plants, play big roles in polluting the environment by sending great amounts of toxic waste into the ozone layer. Effective energy conservation, using highly efficient materials and systems, will reduce the cost for renewable energy (GGGC, 2006). Materials and Resources (MR) criteria aim to minimize the use of non-renewable construction materials and resources such as energy and water, and to maximize the use of recycled materials, modern resource-efficient engineered materials, and resource-efficient composite type of structural systems wherever possible (Zeigler et al., 2003).

The impact of BIM on the design practice is significant due to the fact that it raises new ways and processes of delivering design, construction, and facilities management services. Owners are not only demanding buildings to be designed and delivered on time, within budget, and with high quality but also are looking at their services beyond design and construction (Clayton et al., 1999). Based on Kubba (2012) and Becerik-Gerber & Rice (2010), the development of a schematic model prior to generating a detailed building model allows designers make a more accurate assessment of the proposed scheme and identify whether the design meets the functional and sustainable requirements stated by the owner; this helps increase the project overall performance and quality. The advent of BIM, along with the emergence of global challenging issues such as sustainability, requires designers to incorporate basic performance analysis from an early design phase—i.e., special quality analysis, energy performance, social impact and environmental performance—into its framework by further developing the concept of virtual space and virtual building (Kam and Fischer, 2004). An integrated BIM system can facilitate the collaboration and communication processes between project participants in an early design phase to effectively provide a well-performing building during operations (Hungu, 2013). BIM helps owners visualize the spatial organization of the building as well as understand the sequence of construction activities and the project duration (Eastman et al., 2008). Combining sustainable design strategies with BIM technology has the potential to change traditional design practices and to efficiently produce a high-performance design for proposed buildings. BIM can be used to support the design and analysis of a building system at the early design phase. This includes experimental structural analysis, environmental controls, construction method, the selection of new materials and systems, and detailed analysis of the whole design processes.

Since BIM allows for multi-disciplinary information to be superimposed through one model, it creates an opportunity for sustainability measures to be incorporated throughout the design process (Autodesk, 2008). Hardin (2009) established three main areas of sustainable design with a direct relationship to BIM. These areas are material selection and use, site selection and management, and systems analysis. Krygiel and Nies (2008) indicated that BIM can aid in the aspects of sustainable design, which are building orientation (that can reduce the cost of the project), building massing (to analyze building form and optimize the building envelope), day lighting analysis, water harvesting (reducing water needs in a building), energy modeling (reducing energy needs and analyzing how renewable energy options can contribute to low energy costs), sustainable materials (reducing material needs and using recycled materials) and site and logistics management (to reduce waste and carbon footprints). Wu (2010) proposed a new methodology based on the integration of BIM and green building rating systems. A framework of BIM-LEED was established to prepare the theoretical foundation for pragmatic solutions based on the match-up of LEED certification requirements with the functionality inventory of popular BIM software solutions to support integration. He considers BIM-LEED application through two modules: “Design Assistance” and “Certification Management”. The “Design Assistance” module took advantage of BIM tool’s Application Programming Interface (API) to provide designers with an off-the-shelf LEED knowledge that is built into the BIM tool to ensure the design is LEED-oriented. The “Certification Management” module is a web application built upon an open source Web development platform, which uses Apache as the Web server, MySQL as the relational database management system and PHP as the object-oriented scripting language that focused on managing project information, LEED documentation and submittals for certification purposes. As Wu (2010) described, BIM-LEED integration is feasible with considerable constraints. It should accommodate the requirements of different team members with specialized assistance at different stages of the project delivery process.

LEED takes into account not only social and environmental factors but also financial outcomes. Davis Langdon, An AECOM Company is a construction consultancy company founded in 1919 and working in over 18 countries worldwide. In a cost consulting firm, this company studied and evaluated the cost per square foot of 138 buildings, out of which 93 buildings are non-LEED certified and 45 are seeking LEED certification. The study compares the construction costs of buildings where LEED certification was a primary goal to similar buildings where LEED was not considered during design. The building types that have been analyzed include - academic buildings, laboratories and libraries, community centers and ambulatory care facilities. All costs were normalized for time and location differences in order to ensure consistency in the comparisons. The overall conclusion shows that comparing the average cost per square foot for one set of buildings to another does not provide any meaningful information for any individual project to assess the cost impact of incorporating LEED and sustainable design. The normal variations between the buildings are sufficiently large so that the analysis of averages is not helpful because buildings cannot be budgeted on averages.

Matthiessen and Morris (2004) conducted a comprehensive cost database and budget methodology for green buildings. In their study; they analyzed the cost for each point applicable to the selected project and the level of point achievement for 61 LEED seeking projects. They plot the relationship between the percentage of the points that may be achieved by the projects on the (y) axis and the LEED-NC points on the (x) axis. LEED-NC points would be counted in the project only if they were included in the design and budget of that project. For instance, in energy and atmosphere, the minimum percentage of energy cost reductions for the first three credits are 10.5 percent, 14 percent and 17.5 percent respectively. For new buildings and for renovations, those percentages are 3.5 percent, 7 percent and 10.5 percent respectively, which can be achieved with relatively little cost. In the material and resources (MR) category, Certified and Silver projects tend to achieve 4 out of 13 points, which are MR 2.1 and 2.2 for waste management, MR 4.1 for recycled content and MR 5.1 for locally manufactured material, because the actual specification for these points is neither difficult nor costly for most projects. Gold and Platinum achieve 8 or more. Most projects are unable to meet the reused and renewable materials points (MR 3.1 and 3.2 and MR 6) because of the percentage of building materials required and the cost. The most points sought are the indoor environmental quality category points, because they have no or little cost impact, but they need strong commitment.

Cost data vary depending on the building type, region, size, and any other criteria that may be involved in the project. Northbridge Environmental Management Consultants (NEMC) (2003) determined that LEED adds between 4 percent and 11 percent to construction costs. More than half of these costs are for green design and construction features; the remaining costs fall outside the range of construction costs known as "soft costs", which is the focus of this paper. Soft costs include incremental costs for designing, commissioning the project, Energy Modeling for the project, documenting compliance with the various criteria selected, and LEED application fees.

Participating in the LEED process adds time and effort to the design and specification phase of a project because designers or LEED consultants must assess the project's design and specifications to reflect any additional requirements in order to attain the expected LEED Certification. R.S. Means publisher (2014), which provides cost data for all aspects of building projects, considers that the design costs for green buildings represents 5 percent of the project construction cost as illustrated in table 1. The range for this additional cost is 0.4 percent to 0.6 percent, whereas the traditional design cost ranges between 8 percent and 12 percent of the construction cost (NEMC, 2003). Commissioning is a prerequisite for LEED certification. It involves an outside team, not part of the project's design and construction team, to ensure that the fundamental elements and systems of the building comply with the LEED guidelines. There is an extra point for additional commissioning. Commissioning costs depend on both the complexity and the size of the project. The cost can be higher for more complex buildings such as laboratories. NEMC (2003) found that the commissioning cost is about 1 percent of the total construction cost as shown in table 7.1. However, various construction firms consider the commissioning costs to be in the range of 0.5 percent to 1.5 percent. R.S. Means considers it to be between 0.5 percent and 0.75 percent of the construction cost, the Weidt Group, the company for energy decision makers℠ in US, thinks that commissioning cost ranges between 0.75 percent and 1.5 percent of the total construction costs and the Oregon Office of Energy states that a typical range for commissioning cost is from 0.5 percent to 1.5 percent of the total design and construction costs.

Energy modeling is another prerequisite of the LEED process. It is a smaller part of the soft costs. Energy modeling adds about 0.1 percent to the total construction costs, as presented in table 7.1 (NEMC, 2003). Documentation is the largest obstacle that project teams encounter when working with the LEED process. Proper LEED documentation is necessary for certification. The costs for this documentation depend on the experience of the team involved in documenting the LEED process, regardless of the project's size. After conducting several research projects, NEMC (2003) found that the documentation cost ranges between $8,000 and $70,000 per project, which is an average of 0.7 percent of the construction costs with a range between 0.5 percent and 0.9 percent for typical projects.

Table 7. 1. Sub-total Estimated Soft Cost

Type of Cost	Estimated cost Percent*	Purpose
Design Cost	0.5 percent	Estimate required additional design cost for green buildings
Commissioning	1 percent	Basic commissioning required
Documentation	0.7 percent	Extensive documentation required to indicate how each LEED point was met.
Energy Modeling	0.1 percent	Estimated savings beyond national energy code is required.
Total	2.3 percent	

*Estimated cost as a percentage of the construction costs.

Project registration in CaGBC is the first step towards earning LEED certification, which provides access to LEED's online and credit interpretations. The cost for registration and certification is cheaper for CaGBC members. Certification cost depends on the size of the building and the building type. The details of these fees are provided in table 7.2. There is also another optional soft cost, which is the green building consultant cost. This cost is applied when a consultant is hired to work throughout the process to secure materials, bid specifications, and documents. This cost is not included in the calculation of the total soft cost, because this is an optional cost.

Table 7. 2. Registration and Certification Cost for LEED-NC (CaGBC, 2014)

	Registration		Certification	
	Member	Non-member	Member	Non-member
Standard Review				
2,500 m^2 or less	$600	$900	$4,800	$6,500
2,501-25,000 m^2 (per additional m^2)	$0.14	$0.20	$0.85	$1.15
25,001-150,000m^2 (per additional m^2)	$0.05	$0.06	$0.25	$0.30
>150,000 m^2 (per additional m^2 for certification)	$10,000	$13,000	$0.15	$0.20
Split review: Design review				
2,500 m^2 or less	See standard review	See standard review	$3,890	$5,800
2,501-25,000 m^2 (per additional m^2)	See standard review	See standard review	$0.45	$0.6
25,001-150,000 m^2 (per additional m^2)	See standard review	See standard review	$0.13	$0.16
>150,000 m^2 (per additional m^2 for certification)	See standard review	See standard review	$0.08	$0.10
Split review: Construction review				
2,500 m^2 or less	n/a	n/a	$3,890	$5,800
2,501-25,000 m^2 (per additional m^2)	n/a	n/a	$0.45	$0.6
25,001-150,000 m^2 (per additional m^2)	n/a	n/a	$0.13	$0.16
>150,000 m^2 (per additional m^2 for certification)	n/a	n/a	$0.08	$0.10

Accordingly, the total soft cost calculation from tables 1 and 2 for LEED-NC will be as it is shown in table 7.3.

Table 7. 3. The total soft cost calculation formula based on CaGBC

For LEED-NC CaGBC member	2.3 percent of total construction cost + registration fees (either $600, $0.14/ m^2, $0.05/ m^2, $10,000) + certification fees (either $4800, $0.85/ m^2, $0.25/ m^2, $0.15/ m^2)
For LEED-NC CaGBC Non-member	2.3 percent of total construction cost + registration fees (either $900, $0.2/ m^2, $0.06/ m^2, $13,000) + certification fees (either $6500, $1.15/ m^2, $0.3/ m^2, $0.2/ m^2)
For LEED-NC CaGBC member(Design View)	2.3 percent of total construction cost + registration fees (either $600, $0.14/ m^2, $0.05/ m^2, $10,000) + certification fees (either $3890, $0.45/ m^2, $0.13/ m^2, $0.08/ m^2)
For LEED-NC CaGBC Non-member (Design View)	2.3 percent of total construction cost + registration fees (either $900, $0.2/ m^2, $0.06/ m^2, $13,000) + certification fees (either $5800, $0.6/ m^2, $0.16/ m^2, $0.1/ m^2)
For LEED-NC CaGBC member (Construction View)	2.3 percent of total construction cost + certification fees (either $3890, $0.45/ m^2, $0.13/ m^2, $0.08/ m^2)
For LEED-NC CaGBC Non-member (Construction View)	2.3 percent of total construction cost + certification fees (either $5800, $0.6/ m^2, $0.16/ m^2, $0.1/ m^2)

This paper describes the development of a model that integrates BIM with LEED certification system and cost estimating for sustainable buildings. The model will be used at the conceptual design stage of the project by designers and owners. It automatically provides detailed information about the sustainability of the proposed buildings. It enables users to calculate the points that can potentially be earned based on the green building certification system (LEED-Canada) during the design process. Also the model can calculate the soft cost that includes the fees required to register and to get the LEED certification for the proposed sustainable building project at the conceptual stage by using the API of BIM tool after modifying it. Using the proposed automated model at the conceptual design stage of the project enables designers and owners determine the products that best meet their needs, evaluate their potential points based on the environmental rating systems, and provide the necessary outputs in an easy, quick and convenient way.

7.3. Scope and significance of the study

Different tools are available to analyze the sustainability features of building projects. These tools affect the selection of the proper buildings' components that may help in achieving certain LEED credits. However, these tools are limited to evaluate a small portion of the LEED credits requirements for New Construction projects. They are not directly linked to a specific credit in order to know whether it has been achieved or not. Furthermore, tools used for LEED decisions related may look at different sets of data and building characteristics to test the sustainability of the selected materials and building geometry (Barnes and Castro-Lacouture, 2009). As stated by Krygiel and Nies (2008), "many of the tools used to measure the impact of sustainable design strategies are not directly accessible within a BIM model itself; therefore, data needs to be exported to another application or imported from a data source."

The integrated model proposed in this paper, is linked to BIM tool, which is Autodesk Revit Architecture© in the format of a plug-in. Authors decided to use Revit because it is widely used in the construction industry. All the information already presented in the model, such as project information and LEED parameters of the building components, are stored in an external database, which is connected to BIM tool. The plug-in optimizes the LEED decisions by automatically providing designers and project team with information that identifies whether the current design meets a certain credit requirement (i.e. Materials and Resources (MR) and Energy and Atmosphere (EA)) or not.

Estimating the costs for registration and certification will also be automated through the use of the developed plug-in so that design teams and owners can decide whether this additional cost is worth achieving the credit while considering the overall budget of the project.

7.4. Methodology

One of the expected contributions of this proposed research is the development of an integrated model that calculates the potential LEED points that the materials and components used in the design can accumulate in an attempt to help the design team select the best type of sustainable components for proposed building projects based on owners' priorities and sustainability principles. Traditionally, experts choose materials based on their characteristics or by using the information of the ones used in previous projects, which may cause multiple problems related to expectations, standards, and owner's budgets. The proposed model also calculates the cost of registering the project to get a specified LEED certification set by LEED Canada as well as the cost for certification. Since the proposed methodology integrates different applications, as represented in Figure 7.1, the development will be implemented through the following four phases:

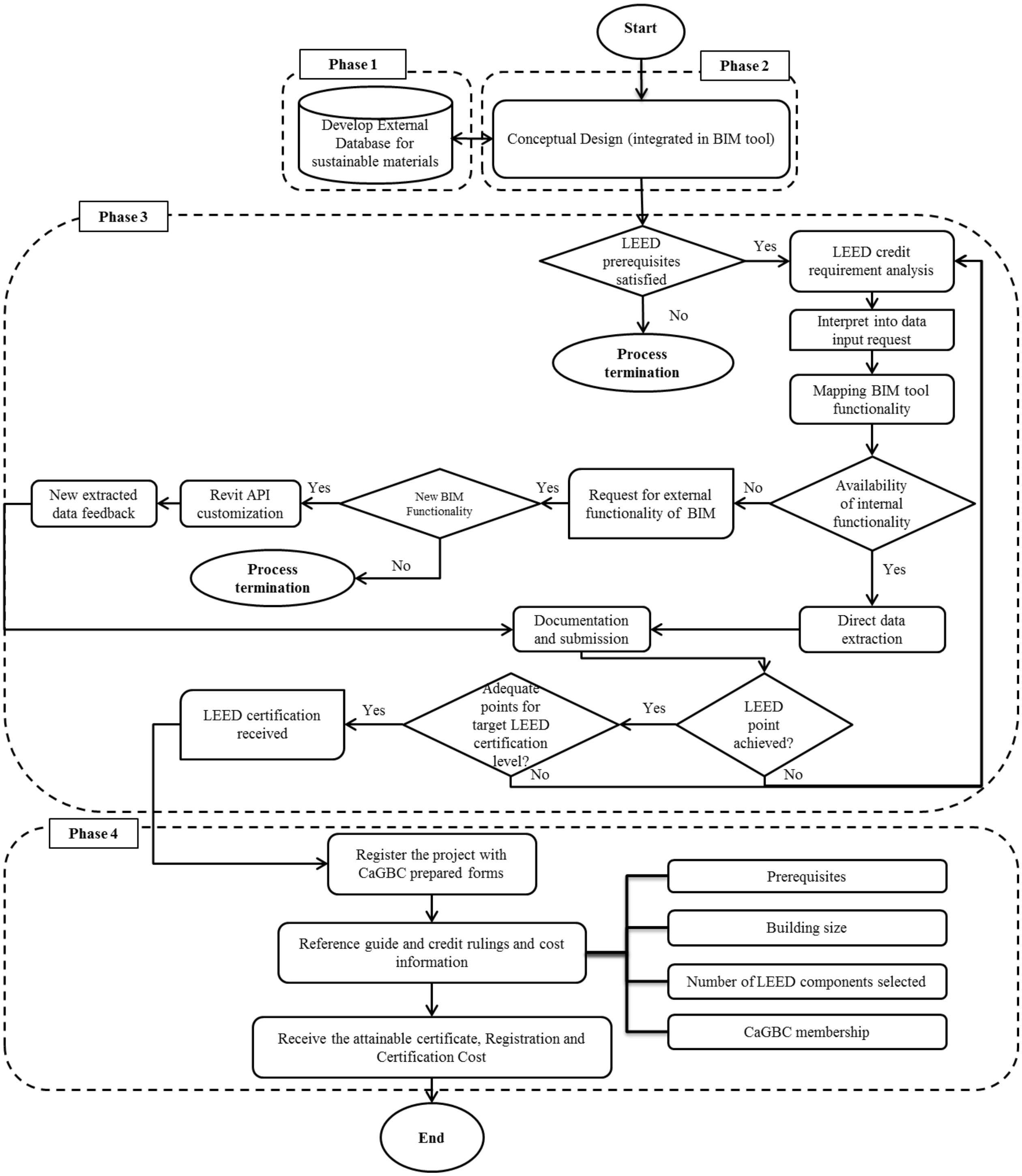

Figure 7. 1. Flowchart of the integration Process

Phase 1 consists of designing the model's relational database needed to design a sustainable building. Loucopoulos (1992) states that a consistent information system depends on the integration between databases, programming languages, and software engineering and that its life cycle incorporates the interrelated technologies of conceptual modeling and database design.

The design and development of this database is accomplished in two steps starting with the conceptual modeling and ending with the physical implementation. First, problem investigation and user needs are recognized based on a comprehensive literature review. Then the database requirements are identified and the conceptual design is carried out. Second, the implementation of the data model requires that the transformation process be made from the conceptual to the logical design (Jrade and Alkass, 2007). Only afterwards the physical implementation is made by creating a list of related tables used to store the collected data based on the selected Work Breakdown Structure (WBS). The information related to the green materials is stored in an external database in the form of predefined design families files (RFA) or Revit files (RVT) that can be recognized by the BIM tool. Thus, in the external database, up to 3,000 design families are collected from the Smart BIM library webpage, suppliers' web pages, as well as published data and are arranged based on the 16 divisions of the Masterformat WBS. Different types of information such as details about the materials used, suppliers' contact data, assigned keynotes, potential LEED points and assembly codes are stored in the external database.

In order to establish the conceptual design, the model outline and its components are created. Subsequently, a conceptual schema is developed. The conceptual schema is a brief description of the data requirements of users and includes a detailed description of entities, relationships, and attributes (Elmasri and Navathe, 2000). Schema is displayed using a graphical presentation known as an Entity-Relationship (ER) diagram. The input into the model includes information about the project such as: Project Name, Project Address, Owner Name, Total Area, Total estimated Cost, Area per Square Foot, Architect, Estimator, Date, etc.; however, Total Area and Total Cost are the most important inputs for the proposed model, without which the data analysis cannot take place and the results cannot be generated. Furthermore, the user has to select the credits or points that he/she wants to achieve in the project from the selected LEED categories which are: (1) Energy Efficiency and (2) Material and Resources.

Phase 2 focuses on customizing BIM tool (i.e. Revit) to fit the modularity requirements of the model. The first step is to design and implement a 3D module capable of storing newly created families in the BIM tool, and their associated keynotes for components commonly used in building projects by using certified green materials. The module is linked to the database developed in Phase 1. Keynotes are textual annotations that relate text strings to specific elements in the model, which are in turn linked to an external text file. A keynote can be used as an external link to the element itself with specific style and specifications so it can be used as a Revit family. The sixteen Masterformat divisions present the main WBS applied in this research. It is very important to select a unique code for each item that is presented in a separate line in the database to ease and simplify their usage.

Phase 3 includes the design and development of a green building certification module, which is linked to the BIM module. This module contains data collected from suppliers' and publishers' webpages. These data are retrieved from the created model by developing and using the sustainability evaluator plug-in that is loaded into BIM tool. In the sustainability evaluation results, there is detailed information about every component, which includes the potential LEED points that can be gained if these materials or components are used in the design. This information is stored in the external database of the BIM tool. The design team can input endless information to be carried with the materials. The plug-in developed for EA and MR credits will rely on these parameters to query cost information. The most important information will serve the need of knowing which LEED credit is applicable to achieve a specific credit. This proves that the optimization tool should be a feature in any new version of BIM tool aimed at designing sustainable buildings. Therefore, when designers model the design for a proposed building in 3D and select any of these sustainable materials or components, the potential LEED points gained by these selected items are identified and stored in the schedule associated with the BIM model. Afterwards, users will add up these LEED points to identify the potential number that the proposed building can earn and accordingly its potential level of certification (Certified, Silver, Gold, or Platinum).

When designers design 3D models for proposed building projects and select any of the sorted sustainable materials or components, the LEED points potentially gained by these selected items are identified and stored in the schedule associated with the model. The module developed in this phase is integrated into BIM tool to automate the process of identifying the required number of points that must be accumulated based on the selected LEED certification level.

Phase 4 focuses on calculating the associated registration cost of the project to get the LEED certificate and its related certification costs. The LEED process consists of three steps: (1)

project registration, (2) technical support, and (3) building certification. Only buildings certified by CaGBC under the LEED Green Building Rating System may be considered as LEED buildings. LEED certification is a third party (CaGBC) confirmation of achieving green principles. The first step in the LEED process is to register the project with CaGBC and receive orientation materials. Registration during the pre-design phase is highly recommended. Helpful resources are available for users such as LEED Letter Templates, Credit Interpretation Request (CIR) access, and on-line project registration. The second step comes in the form of a Reference Guide and Credit Rulings. In some cases, the design team may encounter questions about the application of a LEED prerequisite or credit to a specific project. The owner should first thoroughly consult the Reference Guide. All this support is available through the credit rulings page on the CaGBC web site. The third step is to give the building its attainable certificate; in order to ensure qualification for the specific certificate the application review must be done. This review can take anywhere from six weeks to few months. There are several opportunities for response and request throughout the review stages (administrative, preliminary technical and final technical reviews).

There are 4 specific criteria for new buildings construction: (1) Prerequisites for the LEED Category; which consist of 7 new building prerequisites as shown in table 7.4. These prerequisites have to be met before one can start selecting the LEED components.

Table 7. 4. New Construction Prerequisite

Number	Code	Description
1	SS Prerequisite 1	Construction Activity Pollution Prevention
2	EA Prerequisite 1	Fundamental Commissioning of Building Energy Systems
3	EA Prerequisite 2	Minimum Energy Performance
4	EA Prerequisite 3	Fundamental Refrigerant Management
5	MR Prerequisite 1	Storage and Collection of Recyclables
6	IEQ Prerequisite 1	Minimum Indoor Air Quality Performance
7	IEQ Prerequisite 2	Environmental Tobacco Smoke (ETS) Control

(2) Building Size: part of calculating the certification cost is based on the building area (size). There are four size categories for the building size, which are: a) Building Area Less than 2,500 m^2, b) Building Area between 2,501 m^2 and 25,000 m^2, c) Building Area between 25001 m^2 and 150,000 m^2, and d) Building Area more than 150,000 m^2. (3) Number of the selected LEED Components Selected: this will affect the expected type of certification. Each certification type has a minimum and maximum number of points. The total number of points achieved has to be within the ranges listed in the literature review. (4) CaGBC Membership: the status of the

project's owner will affect the calculation of the registration and certification cost; for members, cost will be less as shown in table 7.2.

The Conceptual development of the methodology is depicted as a data flow diagram. This data flow diagram begins with the data entry, which consists of inputting all the information required for the calculations in the data analysis phase. The input consists of: Project Name, Project Address, Owner Name, Architect, Estimator, Number of Stories, Total Area, Total Cost, Area per Square Foot, and Date. The data entry is done in an input screen. Once the user chooses the type of building a new screen will appear showing the different LEED certification types. The user then has to select the LEED components for each of the building types (which are either New or Existing) from the LEED categories starting by the EA, then IEQ all way to the WE.

As the user select a category, a new screen opens when the user will choose from a list of credits associated with that category. The user may choose none or many credits depending on his/her requirements. The user is then guided to select his membership status. For a member of CaGBC the soft cost is less if compared with the ones of a non-member who has chosen the same number of credits as that of a member of CaGBC. This soft cost is a part of the model's output, which also consists of the Accumulated Selected Points and the LEED Certificate Type.

7.4. Model Implementation & Validation

Since the LEED rating system and all the credits information are completely external to the BIM tools environment (i.e. Revit), it is very difficult to count on their functionalities to achieve the goals of the integrated model. For this reason, API will be used to interrelate the external applications into the BIM tool's platform. To create an API-based plug-in, in the BIM tool, it is necessary to specify an entry point types in the add-in DLL of the BIM tool. In this way, the plug-in will run automatically from the BIM tool's External Tools menu-button to provide designers access to the database that is linked to BIM tool, which indicates LEED integration related to the credit requirements and list of sustainable building components with their associated LEED credits information. The LEED information is integrated into BIM tool to help designers make LEED-informed design decisions. Combining the customized LEED project template, the LEED drawing sheets and the internal LEED knowledgebase major design assistance. Whenever a change is made to the model component, the schedule/ quantity table in BIM tool will be updated correspondingly, and vice versa. The categories in BIM tool are collections of interrelated family types of building components. For instance, the category "Walls" captures all wall instances in the model, regardless of the shape, size, materials and other features of the wall. For each category, there are definitive parameters, which are called "fields", to comprehensively describe the characteristics of a model component. More importantly, if the project team wants to attach more details, BIM tool is flexible in allowing customized parameters to be added into the existing schedules/quantities fields. Arguably, the most valuable parameter to add is the so called "Shared Parameter". The purpose of using a shared parameter is always associated with adding specific data that is not already predefined in the families or projects. The appropriate circumstances for using shared parameters for LEED credits compliance have been identified in the integration framework summary. The Material & Resources category, for instance, is selected for the application of shared parameters. Terms such as "Reused", "Post-consumer", "Pre-consumer", "Regional", and "Rapidly Renewable" specify the materials' features, and should be defined in the LEED project template in BIM tool. Currently, BIM tool (i.e. Revit) supports direct data export through Open Database Connectivity (ODBC) to Microsoft Access and Microsoft Excel. However, both Microsoft Access and Excel are widely used as database management system. Meanwhile, for the BIM Module, it is possible to export the project's design information through ODBC into a predefined Excel database. Unfortunately, the current BIM tool ODBC export does not extract the user defined data. Instead, it strictly controls the export with predefined tables and data types. MR credits, including list of subcategories from MRc1 to MRc7, which all deal with unique material properties that contribute to sustainability. These properties are not predefined in the BIM tool platform and thus require customization in its external database. Simply put, in order to calculate the value of materials that satisfy a certain criterion, which could vary among "reused", "recycled", "regional", and "rapidly renewable", it is desirable to tag the materials in the building information model with such features. For every building component, that credit information is input by authors in the database, which is connected to BIM tool. During the development of the shared parameters, such as MRc5: Regional Materials, it is noticed that in order to tag certain products as "Regional", the project team needs to know where the material suppliers are located, and how far they are from the project's location. To solve this problem, a distance calculator plug-in has already been created by the authors (Jalaei and Jrade, 2014) and embedded in Revit as part of the design assistance module. The developed plug-in uses the API of Google Maps to calculate the distance between the location (origin) of the materials' suppliers and the location of the project (destination) once the required postal codes are entered by the user. Then the distance between the two postal codes is automatically calculated and the result is displayed in kilometres. Since postal codes are commonly available information for all building products, it becomes handy for the project team to use this calculator to determine whether or not a product is regional.

Whereas for the development of the LEED registration and certification cost calculator, in any database application, each of the tables requires a source to get data into them and retrieve the data at a later time. The primary way to get data into tables is to use data entry forms. The primary way to display data in tables is to use queries. The design of any database consists of four major steps. 1) Creating the tables, 2) Finding the relationship between the tables (relationship), 3) Entering data into the tables (forms) and 4) Getting data from the tables (queries). The developed database of the proposed model consists of 21 tables that store project information, new construction categories, estimated subtotal soft cost, the actual cost (registration and certification cost), the building certification cost, and the LEED certification categories. Figure 7.2 shows a design view of a sample table created in the database.

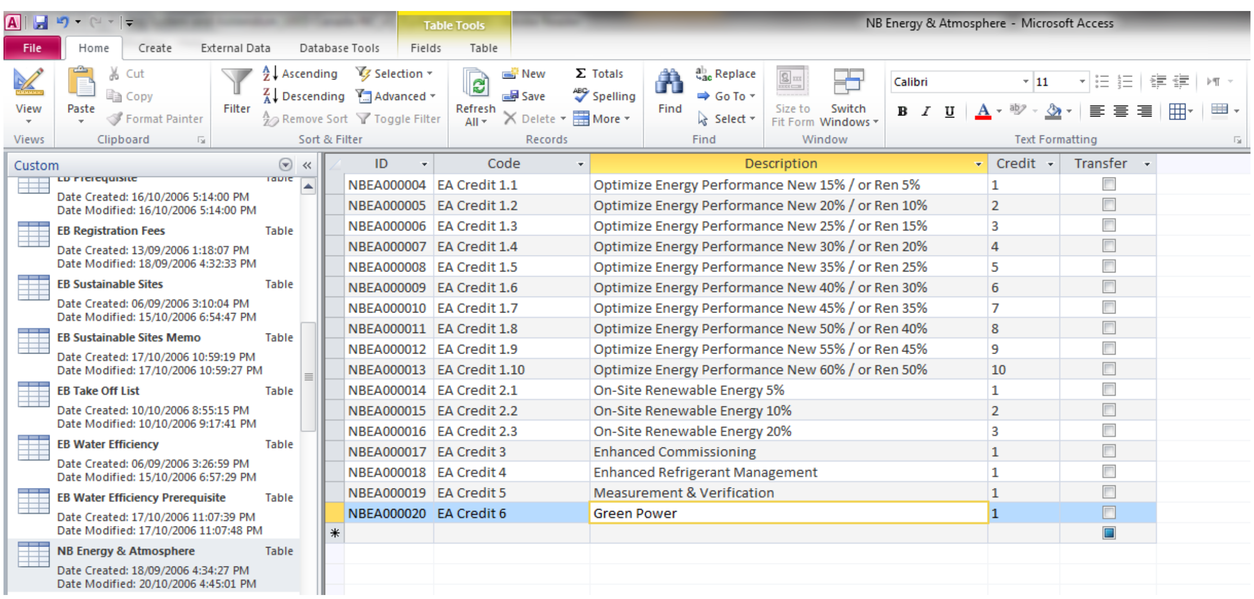

Figure 7. 2. Microsoft Access Table Design View

An alphanumeric coding system is used to create the primary keys, which contains ten digits; the first part refers to the category name and type and the second part is a number to keep the place.

The most important feature in a relational database is having all the tables' related one to another. Relationships are used to tie the tables together.
Although there are three different types of relationships that can be used to related tables, in this model only one type is used, which is the one- to- one relationship, where each table can have only one matching record in the other table. It is sometimes used to store information that applies only to a subset of the main table.
Queries select records from one or more tables in a database in order to be viewed, analyzed, and sorted on a datasheet. The resulting collection of records, called a dynaset (short for dynamic subset), is saved as a database object and can consequently be easily used in the future. Whenever the original tables are updated the query will be updated as well. An SQL query is a query, which is created by using an SQL statement such as SELECT, UPDATE, or DELETE, and includes clauses such as WHERE and FROM. This type of query is used in this model to retrieve data from one or more tables and display the results in a datasheet where the user will be able to update the records. The data source of a form can be a table or a query.
Figure 7.3 shows one of the forms used in the model.

By running the certification cost calculator plug-in, project general information is entered: Project Name, Project Address, Owner, Architect, Estimator, Number of Stories, Total Area, and Construction Cost have to be entered. Cost per Square Foot is calculated automatically by the model and the date. The Total Area and the Construction Cost are very important, because they will be required later to calculate the total soft cost. After entering these two mandatory information fields the "Continue" tab will be activated. After clicking on "Continue" the other tabs will come into view; clicking on the "New Building" tab gives nine different choices: LEED certification criteria, six LEED-NC categories, and "Continue" and "Back to Project Information" tabs. When clicking on each of the links a related form will appear. The first tab on New Construction shows a list of the four different certification types and the range of the required points to be attained to qualify for each certification.

The next six tabs after clicking "New Construction" are for LEED-NC credit categories. Selecting each of these tabs opens a prerequisites memo that lists what is required to be achieved before the user is guided to the credit details for each category, in order to choose the points required for a specific certification. Because the implementation procedure for the six categories is the same, apart from the different credit and point fields; the new construction Energy and Atmosphere category is taken as a sample.

When clicking on the “Energy and Atmosphere” tab, the prerequisites memo will appear as shown in Figure 7.4. The user then has to ensure that these prerequisites are met before proceeding to select the credits. If these prerequisites are not fulfilled, the “Close” tab is chosen so as to exit the model instantly. Otherwise, if all prerequisites are met then the “Continue” tab is clicked to go to the Energy and Atmosphere credit details screen as shown in Figure 8.3. This window allows the user to choose the credits that needed to be achieved in the project.

The first part of the window in the table includes the item ID. The next column is the credit code that is assigned by the CaGBC. The third column describes the credit. And the last column is the number of points that each item can earn.

It is important to be careful when selecting the points, as some items have an upgrade option. When an upper level point field is selected it will include all lower level points under the same credit. For example, if Energy and Atmosphere credit 1. Optimizing Energy Performance is selected it has a different scale depending on the building type (new construction or it is a major renovation building as in Figure 7.2; so if EA Credit 1.7. Optimize Energy Performance for new construction with 31.5 percent cost saving is selected; a total of 7 points will be automatically accrued because it adds all the cost saving points under 31.5 percent. Thus, choosing an EA Credit with a cost saving of less than 31.5 percent along with the highest (in our case EA Credit 1.7) is not allowed in this model, as the credit scores will be replicated.

If “View the Takeoff List” icon is selected the LEED component (credits) screen comes into view, and it includes all the points that are selected from different categories. Next, click on the “Continue” tab; would calculate the total soft cost. A confirmation message will appear about the project area that we entered earlier in the project information screen. This message will prompt the user to select the membership status (if a member of CaGBC or not) because that will affect the registration cost.

Finally the LEED certification status is stated based on the accumulated points. However, if the total of the points achieved is less than the minimum amount required for the LEED certified type, then the LEED certification field would be blank.

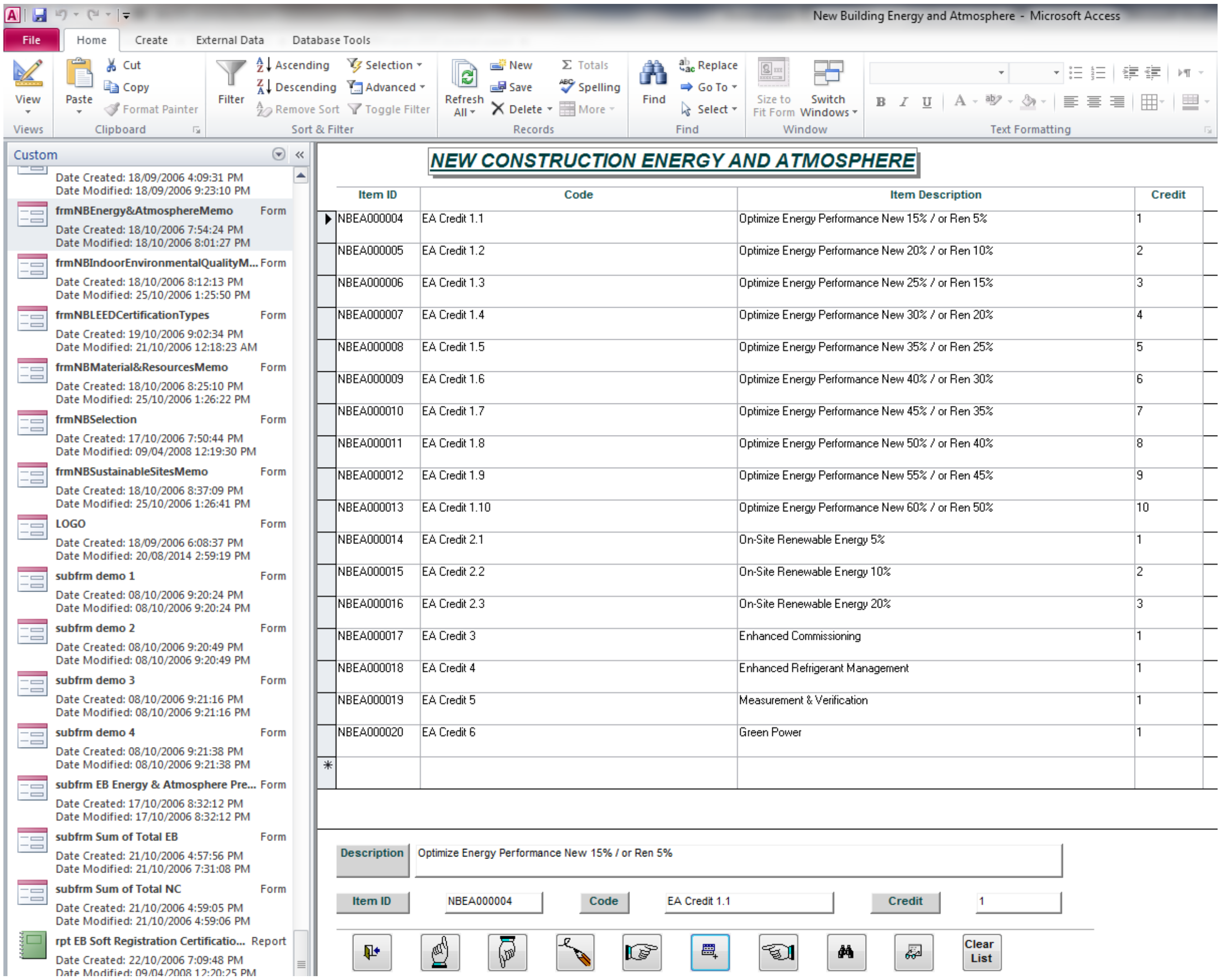

Figure 7. 3. Energy and Atmosphere credit details snapshot in Microsoft Access template

Figure 7. 4. “Energy and Atmosphere” prerequisites memo

To validate this model, its performance is examined through the use of an actual four floor residential complex project with capacity of around 172 people (occupants) that is under design in the city of Toronto. The proposed construction site has a total area of 30,138 ft^2 (2,800 m^2) and the building's gross area is 114,206 ft^2 (10,610 m^2). Floors one to three have each 14 units whereas the fourth floor has 11 units. The main concept of the design is that the majority of residential buildings had a central courtyard. They combine the two typologies of the residential buildings (i.e. central courtyard and terraced houses). In densely populated areas, a courtyard can provide privacy for a family, a break from the frantic pace of everyday life, and a safe place for a children's playground. To mediate the private and semi-public dimension, the building project is going to be built around spaces designated for sports and recreational activities, but at the same time these spaces can be modified for a specific use. The authors created a 3D conceptual design of the current project where its associated sustainable components and materials were selected from the developed database. The components used in the design of the case building had their sustainability specifications as being part of the plug-in's database. Every component, such as the floor, walls, the roof, and windows has its associated LEED information linked to the families of the BIM tool, which includes the manufacturers' web pages and contact information. Figure 7.5 shows a rendered snapshot of the proposed sustainable residential building, which was created using the developed model previously described.

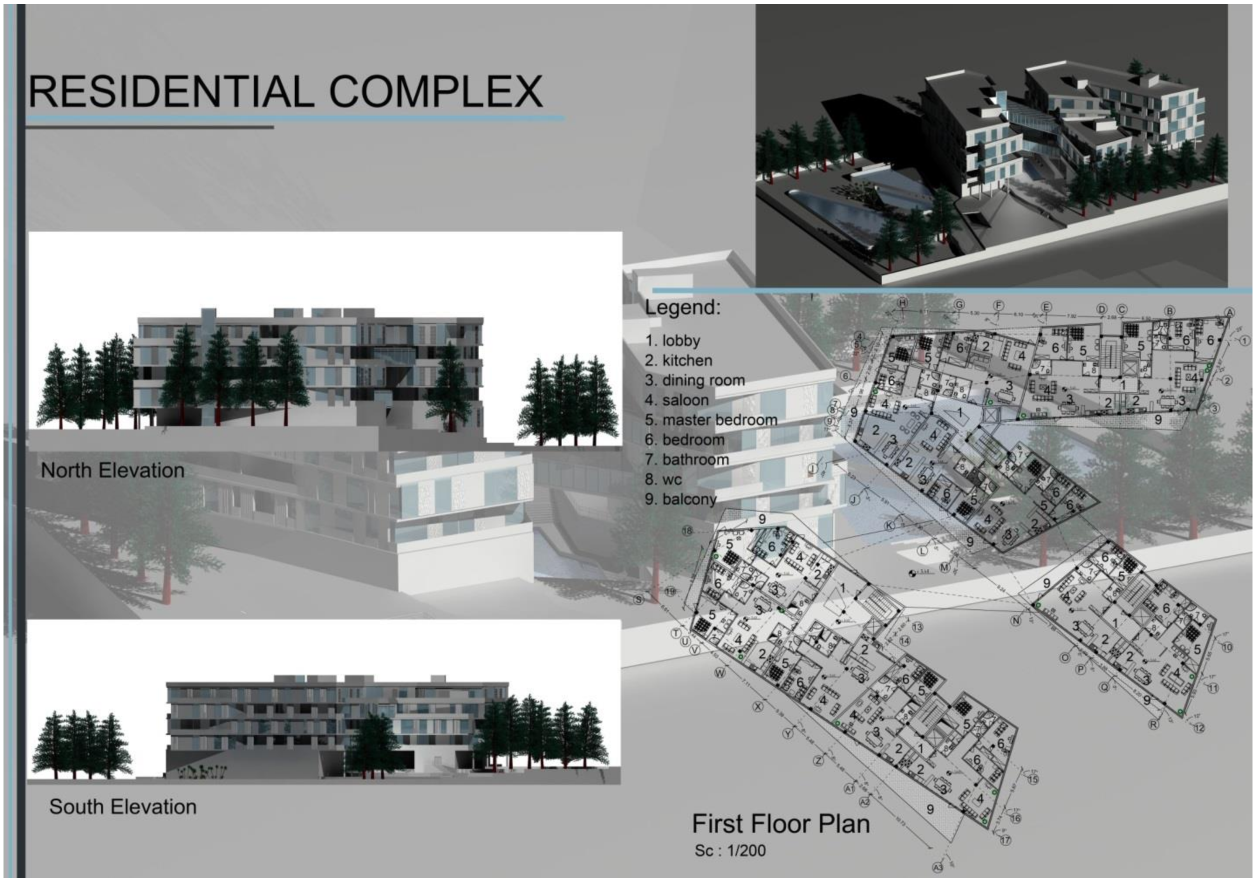

Figure 7. 5. Snapshot of the sustainable case building model (Residential Complex)

During the design of the case project, the designer needs to make a decision on the selection of materials from different alternatives for the current design, such as choosing the best type of materials for doors, roofs, ceilings, walls, windows, and floors and wants to know the potential LEED points that every component can earn. The designer is also concerned about estimating the soft cost of the project. To start, we will use the developed LEED plug-ins in BIM tool, which is in this case Autodesk Revit. After running the plug-in, there are few drop-down menus that contain the assembly group list, the manufacturing company, and the product line of each company, which has to be selected by the user based on the products that are applied to the design. The plug-in reads the list of sustainable building components from an external Excel spreadsheet, which is developed to store the exported materials take offs and shared documents using the ODBC format. To run the plug-in the user must click on the LEED result tool bar. The final results will be presented as a list of building components and their associated credits they can potentially earn. Figure 7.6 shows the list of materials and components used in the case building for both MR and EA credits.

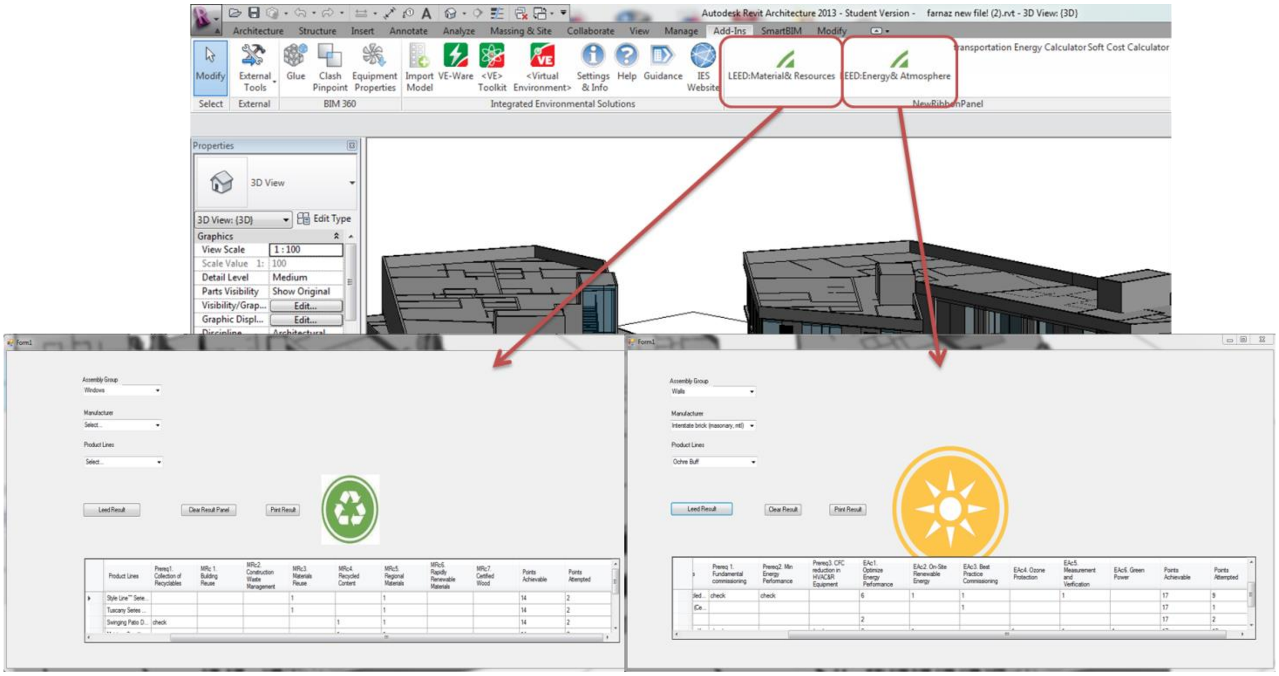

Figure 7. 6. Snapshot of MR and EA credits the model can potentially earn by using the developed plug-in

The distance calculator embedded in the transportation energy plug-in, as stated in the development part, shows the location of the manufacturing company. As shown in figure 7.7, all the assembly groups for this case building can be purchased within a distance of 800 km (500 mi) from the project site. In this case they are eligible to earn the potential points for regional materials. After reviewing the potential LEED credits that the used components can earn, and by using the soft cost calculator plug-in, a user will be able to calculate the total LEED points of the project as well as calculating the registration and certification costs. By running the plug-in, a form is opened, where the user is needed to input the general information for the project, as shown in figure 8.8, and by assuming the project team are members of CaGBC, the “Yes, I am a member” tab is chosen, to proceed to the “Total Soft Cost for New Construction”. Figure 7.9 shows the Project Area and Project Construction Cost that was entered by the user. The registration fee is also shown in this screen and this fee is calculated based on the membership status with the CaGBC. The certification fees are calculated based on the project area information provided by the user. The estimated soft cost is calculated according to total construction cost, and then the total soft cost is given by adding the registration fee, the certification fees and the estimated subtotal soft cost. Figure 7.9 also gives a summary of the soft cost. A report can be printed by clicking the print icon at the upper left corner. As illustrated in figure 7.9, based on the information provided by the designers and by inputting the project definition, it was found that the total points the case building can earn for floors, roof, walls, doors and windows is 47 points, which shows that this building has a potential to be gold certified if it is registered for a LEED certificate. The report as shown in figure 7.8 shows the distribution of cost for registration, certification and total soft cost of the project which is $315,814.

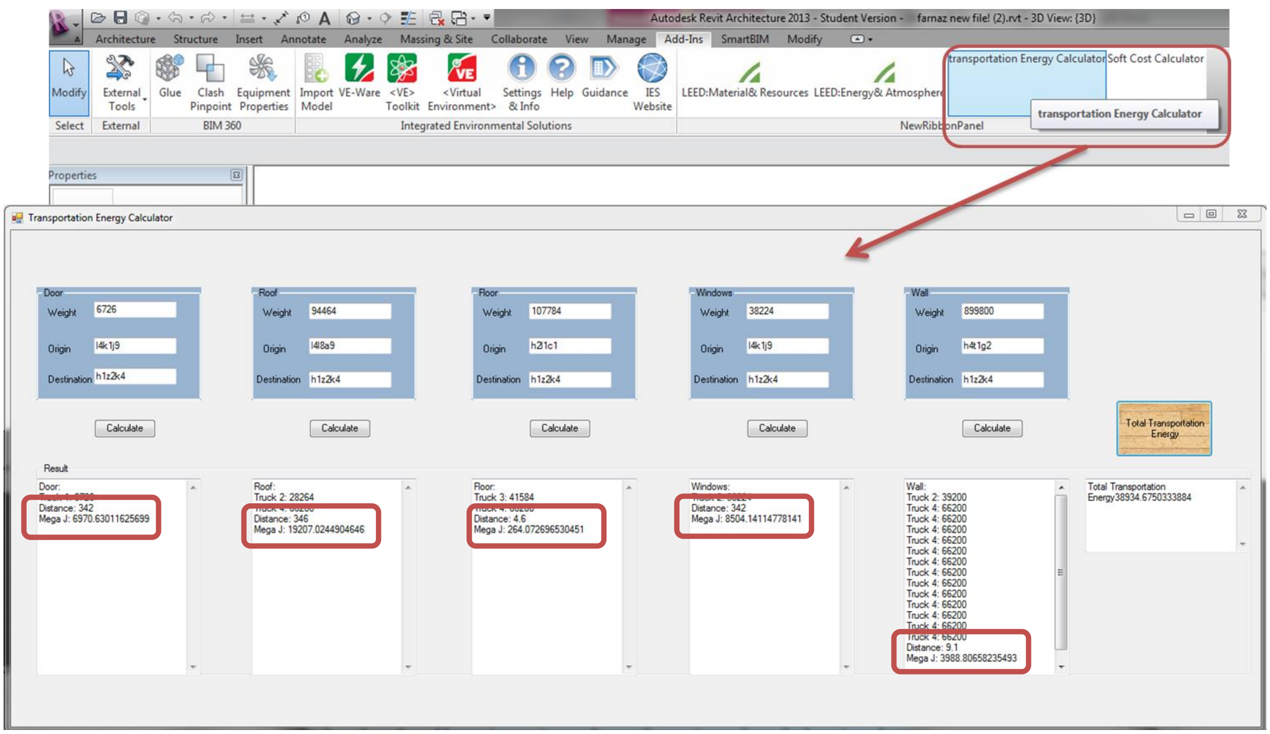

Figure 7. 7. Distance Calculator plug-in to illustrate regional materials (Jalaei and Jrade, 2014)

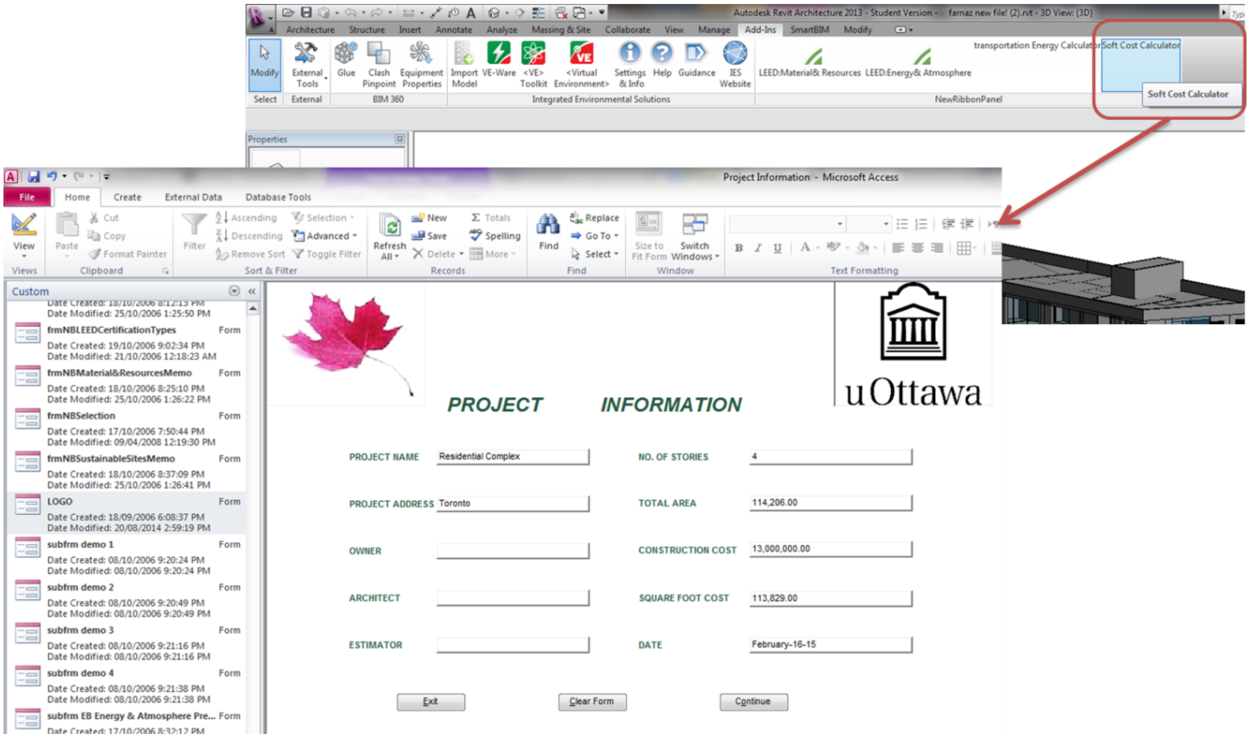

Figure 7. 8. The snap shot of Soft cost calculator plug-in and the input form

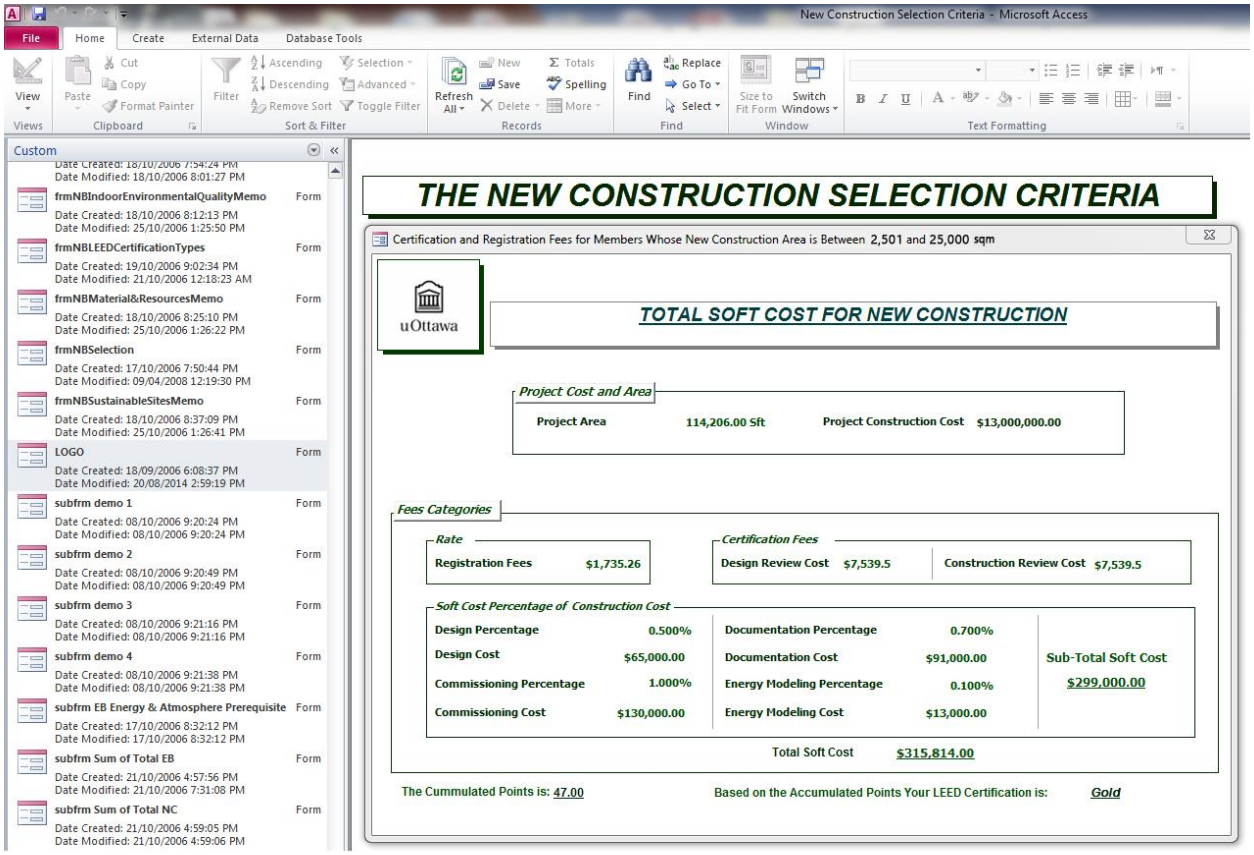

Figure 7. 9. The snap shot of Soft cost results

7.5. Conclusion

This research evaluates the implementation of BIM by representing a computer model that automates the process of identifying the required number of points based on selected LEED certification categories, accumulates the total selected points as well as suggests the qualified certification. Furthermore, the developed model estimates the total soft cost associated with the certification. During the match-up LEED credit/certification process, the compliance as well as submittal requirements of the LEED credits were analyzed and interpreted into certain data requests, including qualitative and quantitative data types, or both.

The developed model in green building practice reduces one of the biggest barriers for going green by eliminating the documentation process. It is the first model that deals with LEED categories, associated certification levels and soft cost estimation, saves users' time, and reduces users' effort. Also it is a simple point selection method and easy to use. There is no need for the applicants to document and record all points, just the expected points that they may achieve.

Furthermore, the developed model will improve the documentation process. The model concentrates more on the soft cost. Also, it does not analyze the cost associated with the different ways (material or system) that can be used to attain each credit or point.

Overall, this research demonstrated that BIM and LEED integration was feasible with considerable constraints. This model does not include all the LEED products; it includes only LEED-NC and in the LEED credit accumulating plug-in, this model only focused on EA and MR credits, since adding the other features to this developed platform needs more time and effort. The model does not incorporate the cost analysis for each point depending on material and system used besides the project size and cost.

This study looked only at the integration of BIM and sustainability from the LEED perspective, and only one LEED rating system (LEED-NC) was analyzed. The results thus were limited to the LEED instead of the general framework of sustainability. Plus, all the software applications developed in this research were quite generic. More intensive coding will be desirable to turn the results of this study into actual products. Finally, considering the immaturity of the BIM and LEED integration, technical issues were dominant in this research. Nevertheless, in a real world LEED project, the cost-benefit implication of such integration is equally important to determine the best strategy to leverage the certification process using BIM.

Limitation in support for direct data I/O through the ODBC driver is hindering the development of more flexible and creative strategies of information exchange between project team members. The openness of the software APIs also needs to be addressed. Due to the unique circumstances of a project, software users want flexibility to customize the application to better serve their needs in manipulating the model information. APIs provide the critical interface to allow such customization. To achieve well balanced building performance, BIM development needs reinforced efforts at the full spectrum of issues in building design and construction.

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CHAPTER 8

TECHNICAL PAPER V

Integrating Decision Support System (DSS) and Building Information Modeling (BIM) to Optimize the Selection of Sustainable Building Components

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(Submitted in Journal of Information Technology in Construction, Date of Submission: 09/03/2015)

Abstract- One of the challenges in sustainability analysis and its development is the optimum selection of sustainable materials to meet the project's requirements while doing sustainable design. This can only be achieved when project team adopt the use of a strategic approach while selecting the materials, although this could be a complex task for decision makers. Building Information Modeling (BIM) offers designers the ability to assess different design alternatives at the conceptual stage of a project. As a method of integration and through its modeling techniques, BIM can be used to assess the impacts of design alternatives on the energy saving of buildings all over their life. Furthermore, BIM has the potential to help designers select the right type of materials during the early design stage, and make vital decisions when selecting the materials that have sustainable impact on the building's life cycle.

The main purpose of this study is to propose a methodology that integrates BIM with decision-making problem-solving approaches (i.e. Entropy-TOPSIS) in order to efficiently optimize the selection of sustainable building components at the conceptual design stage of building projects. Therefore, a Decision Support System (DSS) is developed by using Multiple Criteria Decision Making (MCDM) techniques to aid the design team decide on and select the optimum type of sustainable building components and design families while doing conceptual design of proposed projects, based on three main criteria (i.e. environmental factors, economic factors—"cost efficiency," and social well-being) in an attempt to identify the influence of design variations on the whole building's sustainable performance.

The multi-criteria procedure embedded in the DSS relies on numerical models to simulate alternative situations, as well as ranking the alternatives and select the best ones based on both the owners' strategic preferences and the availability of sustainable materials in the market. The set of models included in the DSS describes the relationship between sustainability criteria, manufacturers' sustainable materials and the interactions between project team that take place during the design of sustainable building projects. This paper aims at exposing the feasibility of using BIM for analysing the life cycle costs of sustainable buildings at the conceptual stage. The design alternatives suggested by the DSS are evaluated in an integrated environment that joins BIM concept and Life Cycle Cost (LCC) method to analyze the operational cost of the whole building. An actual building project is used to validate the workability and capability of the proposed methodology.

KEYWORDS: BIM, Decision Support System (DSS), Life Cycle Cost (LCC), Sustainable Design, Green Building

8.1. Introduction

The variety of project boundaries, decision-maker preferences, and the availability of sustainable materials make the decision-making process more difficult in terms of sustainable development purposes when designing sustainable buildings. While, owners want to use sustainable products in their proposed building projects, a decision on the ideal ones can be questioned especially when suppliers offer diverse types of green materials.

A typical manufactured product, in the building industry, consists of various components where each of its elements may consist of several materials. In many cases, products' elements, which are furnished by a chain of suppliers, are processed, assembled and finally released to customers (Aumonier, 2013).

The Multiple Criteria Decision Making (MCDM) approach is a well-known branch of the decision-making process. It deals with decision problems under the presence of a number of decision criteria, where a decision-maker needs to choose from either the quantifiable or the non-quantifiable or the multiple criteria. Usually, sustainability objectives are conflicting due to their dependency on each other and therefore, the solution is highly dependent on the decision maker's preferences, which is mostly a compromise. Generally, two different methods are used to solve the MCDM problems, those are: the Multiple Objective Decision Making (MODM) method and the Multiple Attribute Decision Making (MADM) method. MODM deals with many objectives in order to come up with an optimal solution to achieve the set objectives, which sometimes conflict one with another and accordingly makes the goal to attain an ideal solution more challenging and problematic. Whereas in the MADM method the decision maker transacts with alternatives that have variety of performance attributes and factors, which can be either qualitative or quantitative (Shanian and Savadogo, 2006). The MADM method is generally a discrete method, with limited numbers of pre-determined alternatives. It specifies how to process the attribute's information in order to reach an ideal choice. Rao (2007) thinks that this method needs both inter-attributes and intra-attributes comparisons and should involve appropriate explicit trade-offs. To model these attributes, most of the MADM methods are presented through a decision matrix. This matrix consists of: 1) alternatives; 2) criteria; and 3) relative significance of criteria. In this matrix, all the components should be normalized to a comparable scale.

Generally, there are various MADM techniques (i.e., crisp; fuzzy approaches) to use during the decision making process, however in this proposed study, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is used for ranking the alternatives. TOPSIS is one of the objective weighting methods in MCDM; it is a method of compensatory aggregation that compares a set of alternatives by identifying weights and normalizing scores for each criterion and calculating the geometric distance between each alternative and the ideal one, which is considered as the best score for each criterion.

In recent years, with the advancement of technology, applying MCDM methods has become considerably simpler for decision makers and users who are involved in complicated mathematical problems and multiple alternatives. Thus, Decision Support Systems (DSS) are generated to assist in the problem-solving process by combining quantitative data and qualitative knowledge/perceptions; processing information in order to present, compare, and rank potential alternatives; and, ultimately, selecting the one that meets the established decision criteria (Lu et al., 2007). Besides considering the decision-maker (DM) priorities and preferences, the development of a Decision Support System (DSS) can also help DM in financial/non-financial constraints and objectives (Lu et al., 2007). DSS can improve decision makers' efficiency, productivity and effectiveness. It can also facilitate the communication between different parties in an organization and contribute to a quick problem solving.

Building Information Modeling (BIM) is a recent method of approaching the design and documentation of building projects by considering their entire life cycle, including all information related to designing, simulating and operating them through the use of different integrated tools.

Life Cycle Costing (LCC) method is used to estimate the overall costs of a project and to select the design that would provide the lowest overall cost of ownership without sacrificing its quality and function. The LCC evaluation and analysis should be performed early during the design process while there is still a chance to refine the design to ensure a reduction in the running costs later on during the operation stage of the project (WBDG, 2010).

The essential objective of life-cycle costing is to evaluate the possible economics of different alternatives. However, there are other important cost factors beside the initial capital cost that have a significant contribution to the overall cost throughout the life cycle of a project. Some of these factors are operating, maintenance, and repair costs beside the thermal insulation properties and methods that influence the running costs of the project.

While, maintenance and repair costs can be provided by the owners, obtained from a published database, or obtained from the manufacturers (Haviland, 1978), energy efficiency studies should be performed by designers to forecast the operating costs. It is commonly known that Life Cycle Cost is the sum costs of owning, running (maintaining and operating), and demolishing a facility over an assigned period of time, therefore, the LCC equation includes four variables: 1) The relevant costs of ownership: initial cost, running cost, and replacement cost; 2) The future income, such as annual income from renting/leasing the facility and/or its salvage value at the end of the study period; 3) The period of time over which these costs are incurred; and 4) The discount rate (inflation or deflation rate) that should be used to adjust the future costs in order to compare them with the current ones (Alshamrani, 2013).

Lowest life-cycle cost (Lowest LCC) method is the most easily-interpreted measure of economic evaluation in construction projects. Some other methods of economic measurements used are Net Savings (or Net Benefits), Savings-to-Investment Ratio (Benefit-to-Cost Ratio), Internal Rate of

Return, and Payback Period. These are consistent with the Lowest LCC measure of evaluation method if they use the same parameters and length of the study period (WBDG, 2010).

Operational expenses for energy, water, and other utilities are based on consumption, current rates, and price projections. Since energy and water consumption, and building configuration and envelope are interdependent, operational costs are usually evaluated for the building as a whole rather than for any individual building components. Energy costs are often difficult to be accurately predicted during the conceptual stage of a project's life, therefore assumptions must be made about the historical energy usage, occupancy rates, and weather data that impact the energy consumption. At the conceptual stage, data related to the amount of energy consumed by a building can be retrieved from an engineering energy analysis or from some specific computer applications such as eQuest©, Green Building Studio© (GBS) while other applications like ENERGY PLUS (DOE), DOE-2.1E and BLAST cannot be used at that stage because they require more detailed information and data input that usually is not available until later stage in the design process (WBDG, 2010).

This study reviews the different decision-making methods and their applications in selecting sustainable materials. Furthermore, it describes the methodology used to integrate Building Information Modeling concept and Decision Making technique through the development of a model that incorporates a decision support system (DSS), which systematically incorporates the selection of sustainable components and material into a BIM environment. The DSS is based on Building Information Modeling (BIM) principles, and associated with environmental and socio-economic indicators for sustainable development. In particular, the DSS evaluates green building materials provided by different suppliers and suggests the best ones that fit the sustainable design requirements. Furthermore, the model is integrated with LCC method that would help in evaluating and validating the different design alternatives that are recommended by the DSS in order to identify the one that leads to the most effective operational cost (energy cost).

8.2. Literature Review

Standard approaches for decision-making problems are classified into different classes. Lu et al. (2007) list the most significant classes as follow:

• Structured, where the process for achieving the best solution is known as the standard method, which can be described by using statistics for comparing products in terms of cost or quality.

• Unstructured, where problems generally have fuzzy natures in which human intuitions are the basis of most the decision making.

• Semi-structured, where problems are a combination of both the structured and structured ones and the ideal solutions for these problems are based on mixing both the standard approaches and the human judgements.

According to Simon (1977), a decision-making process consists of three phases: "Intelligence", "Design", and "Choice". Several years later, he added, "Implementation" as the fourth phase. It is during the intelligence phase that the problem is defined while in the design phase a model will be presented to define the assumptions where inter-relationships among the variables are identified. The ideal solution will be selected for the defined model during the choice phase. It is also necessary to validate the model by viability tests. After confirming the model's workability, it will be the implementation phase, which is used to solve a real problem. In case of any failure during this last phase the whole process will be repeated starting from the intelligence stage.

Commonly, the decision-making modeling step is considered to be the most fault-finding step in the whole decision-making processes (Simon, 1977). Thus, it is essential to properly define the problem in order to formulate the model. Generally, there are different approaches used to solve the decision-making problems. For instance, Analytic Hierarchy Process (AHP) is a decision-making method that allows decision makers to consider both qualitative and quantitative aspects of the decision-making process (Lu et al., 2007). The Paired Comparison Analysis method is employed in cases where alternatives are related to each other. Yet, Lu et al. (2007) think that this method permits decision makers to consider priorities that are sometimes conflicting to the project demands. Grid Analysis, which is known as a matrix or multi-attribute theory, is an effective approach that a decision maker can cope with many alternatives and criteria. In this method, the criteria and alternatives are first defined, after that the importance of relative factors is identified, and finally decision makers would be able to assign weights to their priorities, which are combined with the importance of each criterion. Another approach is the Decision

Tree model, which is a graphical presentation of the decisions and their potential results. This predictive model consists of data-sets of observations that are connected to each other by a tree structure in the form of nodes and leaves. A leaf demonstrates the expected value of a variable where each interior node stands for a variable (Simon, 1977). Computerized Decision Support Technology is a tool by which the decision maker will be able to employ large numbers of complex models in a short period of time. Furthermore, this technology would help decision makers to share, store, update, and transmit data faster and to reduce the risks of human errors (Lu et al., 2007).

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision analysis method that was originally developed by Hwang and Yoon in 1981. The principal objective of TOPSIS is to select the best alternative with the shortest distance from the ideal alternative (Yoon, 1981). They assumed that if each factor takes decreasing and increasing variations, it makes it possible to find the ideal solution.

In the TOPSIS method, vector normalization eliminates the units of criterion function where vast ranges of material features and their performances are involved. Furthermore, the results can be ranked according to their preferences and their numerical values. This ranking gives a clear comprehension of the similarities and differences between preferential alternatives while other MADM methods (i.e. ELECTRE) show only the ranking values of the alternatives regardless of their differences and similarities. The main pitfall of the pair-wise comparisons in AHP methods avoided. While working with vast numbers of alternatives and attributes, TOPSIS is easier to use and less time consuming.

Due to the variety in MADM approaches, there are different methods available to use for the material selection, these include: TOPSIS, ELECTRE, VIKOR, ANP, PROMETHE, etc. Each of these methods has advantages and disadvantages during the decision-making processes. Therefore, researchers have applied diverse approaches in order to recognise the proper technique. For example, as a practical application, Jahan and Edwards (2013) applied the VIKOR method to select the right type of materials. On the other hand, Peng and Xio (2013) used the ELECTRE decision-making technique for the purpose of selecting the required materials. Recently, Liu et al. (2014) employed the novel hybrid multiple criteria decision-making, which considers qualitative and quantitative factors simultaneously. This method is a combination of both the ANP and the VIKOR approaches.

Based on Mansour et al. (2013), one of the most common techniques is the analytical hierarchy process (AHP) method. This method has been used to select hybrid natural and glass fiber reinforced polymer composite materials for automotive brake lever design. Whilst, Shanian and Savadogo (2006) choose TOPSIS multiple-criteria decision support analysis for the materials selection of metallic bipolar plates for polymer electrolyte fuel cells. Yousefpour and Rahimi (2014) propose the combined AHP-TOPSIS method to select the best coating material for corrosion. Peng and Xio (2013) combine the PROMETHE method with the Analytic Network Process (ANP) under a hybrid environment to select materials. In green supply chain management, Hsu et al (2013) use the DEMETEL method to develop a Carbone management model of materials and supplier selections. Jahan and Edwards (2013) utilize a target based normalization technique for the materials' selection, while Kasaei et al. (2014) apply a quality function deployment method for choosing the aerospace engineering materials.

The impact of BIM on the design practice is significant because it raises new ways and processes of delivering design, construction, and facility management servicing them. Owners not only require buildings to be designed and delivered on time, within budget, and with high quality but they also want to know the cost of running them beyond the design and construction (Clayton et al, 1999). Based on Kubba (2012) and Becerik-Gerber and Rice (2010), the development of a schematic model prior to the generation of a detailed building model allows the designer to make a more accurate assessment of the proposed project and to evaluate whether it meets the functional and sustainable requirements set forth by the owner; this helps increase project performance and overall quality. The advent of BIM along with the emergence of global challenging issues like sustainability, and life cycle cost of buildings, requires designers to incorporate basic performance analyses starting at the early stage of design. Those performance analyses include special quality analysis, energy performance, social impact and environmental performance into a framework of BIM concept by further development of virtual buildings (Kam and Fischer, 2004). An integrated BIM system can facilitate the collaboration and communication processes between project participants during the early design phase to effectively provide a well-performing building later on during the operation phase (Hungu, 2013). BIM concept allows multidisciplinary information to be superimposed within one model by incorporating structural, mechanical, electrical, plumbing and lighting information into a single model (Tucker and Newton, 2009). It helps owners visualize the spatial organization of the building as well as understand the sequence of construction activities and the project duration (Eastman et al., 2008). Combining sustainable design strategies with BIM concept has the potential to change traditional design practices and to efficiently produce high-performance designs for proposed buildings. BIM technology can be used to support the design and analysis of a building system at the early design phase. This includes experimental structural analysis, environmental controls, construction methods, the selection of new materials and systems and detailed analysis of the design processes (Jalaei and Jrade, 2014).

Decision support systems (DSS) have been applied in a many contexts. One approach used a simple form to provide help in managing water uses, identifying water quality problems, evaluating the performance of pollution control programs, and presenting technical information to public, specialist, and non-specialist decision makers (El-Gafy, et al., 2005). The study conducted by Juan et al. (2009) focus on developing an integrated decision support system for office building renovation that not only assesses current conditions but also provides solutions on implementing sustainable renovation for decision makers. These solutions must optimize the trade-off between improved quality and investing cost for each suggested renovation action. As for the decision support system, solutions are determined by a novel hybrid approach that combines A* and genetic algorithms (GA). Another study described the implementation of a decision support system, for a large apartment building project, in which clients can make cost based decisions that meet their requirements, while designers can control the costs of both the resource planning and interior design (Lee et al., 2008).

Jadid and Badrah (2012) implemented a decision support system to select the materials for projects under design or construction by consultants and owners. The study focused on issues related to materials approval, selection criteria and materials information management. The described system included database and decision support components. The database can enhance the functionality of the selection process as it provides a source of information to feed into the decision support component. The decision support component relies on the quantitative methods of value engineering. Yang et al. (2013) introduced the development of a multi-criteria decision support system (DSS) to improve the understanding of the best practice's principles associated with the impacts of low-cost green building materials and components. The DSS presented in their study provide designers with useful and explicit information that will aid decision-makers in their choice of materials for low-cost green residential housing projects. The prototype DSS is developed by using macro-in-excel, which is a fairly recent database management technique used for integrating data from multiple, often very large databases and other information sources. Abdallah et al. (2013) presented the development of an automated DSS that is designed to optimize the selection of green building measures, which can be used to upgrade existing buildings. The developed DSS helps minimizing the total upgrade costs required to accomplish a specified LEED-EB certification level such as silver or gold; and maximizing the number of accredited LEED-EB points within a specified budget of upgrade costs. The DSS is designed to identify a set of optimal upgrade decisions that accomplishes these two optimization objectives.

Several studies were done in the past focusing on the application of LCC analysis to sustainable building projects. Alshamrani (2012) study focuses on evaluating school buildings using sustainability measures and life-cycle costing technique. In his paper, he explains the development of a framework that helps school boards to select cost-effective and sustainable structure and exterior envelope types for new school buildings. The selection procedure is represented based on the Leadership in Energy and Environmental Design (LEED) rating system and life-cycle cost analysis techniques for typical structure and envelope-type alternatives. Fourteen different structure and envelope types (e.g., steel, concrete, and wood) are evaluated in various combinations covering both conventional and sustainable alternatives.

Kats et al. (2003) study the "Costs and Financial Benefits of Green Buildings". Cost data was gathered from 33 individual LEED-registered projects (25 office buildings and 8 school buildings) with actual or projected dates of completion between 1995 and 2004. They demonstrate conclusively that sustainable buildings are a cost-effective investment, and accordingly their findings should encourage communities across the country to "build green." They assume a 20-year term for benefits in new buildings' inflation. The results of testing these buildings show an average of 30% reduction in energy use if compared with the consumption associated with the minimum energy code requirements. Where, their energy costs are \$1.47/ft²/yr, which led to cost savings of about \$0.44/ft²/yr and a 20-year present value (PV) of

$\$5.48/\text{ft}^2$. The additional value of peak-demand reduction from green buildings is estimated at $\$0.025/\text{ft}^2/\text{yr}$, with a 20-year PV of $\$0.31/\text{ft}^2$. That report assumes a value of $5 per ton of carbon, indicating a 20-year PV of $\$1.18/\text{ft}^2$ for emissions reductions from green buildings. Moreover, the calculation of rough conservative values for Construction and Demolition in new construction is $\$0.03/\text{ft}^2$ or $3,000 per 100,000 ft^2 for building construction only. To be conservative, the report considers that green buildings experiences on operation and maintenance cost decline on a trend of 5% per year. This equals a savings of $\$0.68/\text{ft}^2$ per year, for a 20-year PV savings of $\$8.47/\text{ft}^2$. Productivity and health values for LEED-certified and silver-rated buildings showed savings of $\$36.89/\text{ft}^2$, while for LEED-gold and platinum buildings show savings of $\$55.33/\text{ft}^2$. The data indicate that the average construction cost for green buildings is almost 2% more, or about $4/ft2, whereas in California this value is substantially less than it is generally perceived. As a conclusion, the NPV for a 20-year time period shows a total estimated savings of $\$48.87/\text{ft}^2$ for LEED-certified and silver, and a total estimated saving of $\$67.31/\text{ft}^2$ for LEED-gold and platinum levels. A common way to determine the green cost is to compare the project's final budget with the initial budget. This tends to include all cost coverages, not only those associated with LEED points. Optimizing the design from an energy/cost perspective can be seen as a selection problem of the best types of buildings components. These components mainly include the roof, floor, doors, windows and walls where their selection is done from a pre-defined list of available alternatives for each of these components (Nour et al., 2012). Ihm and Krarti (2012) use a sequential search technique to optimize the design of residential buildings in Tunisia. They try to minimize the life cycle costs of energy, while increasing the building energy efficiency. Wang et al. (2005) performed a multi-objective optimization and improvement technique for buildings' design. The intend of their study is to assist designers in achieving cost-effective green building design based on the life cycle analysis methodology. Nielsen et al. (2002), Winkler et al. (2002), and Huberman and Pearlmutter (2007) also study in detail the importance of applying life cycle cost analysis and the need for its optimization and modeling challenges. Using Building Information Modeling (BIM) with LCC and energy consumption and analysis during the design stage would lead to an efficient automation in the data flow between different databases, analytical and mathematical applications. Easy access to comparable data gives designers the potential to focus on the operating stage of buildings, as well as improving the optimization of their energy consumptions and expenditures (Krigsvoll, 2007). This study aims on incorporating the total annual energy costs of building(s) through a LCC module that uses inputs from the BIM/gbXML module and then providing the results to the project team to make the right decision. Predicting the annual energy consumption however, is a challenging procedure that requires energy simulation by using weather data, thermal properties of used materials for different building components and information related to HVAC systems and other appliances. It is envisaged that the output of the BIM tool would be input to the energy analysis tool by using the gbXML file format (Bazjanac et al., 2011). The Green Building XML schema — known as "gbXML" — was developed to facilitate the transfer process of the information stored in building information models and to enable the integration and interoperability between different design models and other engineering analysis tools. Furthermore, gbXML facilitates the exchange of building information, which includes product characteristics and equipment performance data between the manufacturer database, the BIM models and the energy simulation engines. One of the benefits of gbXML is its ability to carry detailed descriptions of a single building or a set of buildings that can be imported and used by energy analysis and simulation tools (Kumar, 2008).

The major limitation in using energy simulation tools is the issue of their interoperability with BIM. Another limitation is the lack of information needed at the conceptual stage of the project. Since the lifecycle costs of building elements are provided in the form of annual cost per unit area ($/ft2), it is essential to extract the quantities from the model to estimate the cost of every building component. Then, the overall life cycle cost of the building can be calculated. The literature review confirmed the effect of building performance on its Life Cycle Cost and the need of its optimization. This is achieved by using an integrated BIM platform that would be used to select suitable building components from different alternatives that leads to a minimum lifecycle cost and energy consumptions.

8.3. Scope and significance of the study

It is commonly known that designing a building that is energy efficient is more expensive to construct but its future costs are reduced over the entire life cycle. Even though the efficient co-ordination of people, tools and technology can lead to significant benefits in the quality and performance of buildings, there are many challenges to be faced. An integrated design process, interdisciplinary collaboration, complex design analysis, careful material and system optimization are required to solve this problem (Nofera et al., 2010). Although previous studies described several methods and techniques used by designers to select optimum combination of building components, authors could not find any research that has been implemented with the focus on integrating BIM concept with a decision Support System (DSS) to simulate alternative situations, as well as ranking the alternatives and select the best ones based on both the owners' strategic preferences and the availability of sustainable materials in the market.

Therefore, this research intends to introduce various analytical BIM-based integrations, which can be used during the conceptual design stage to select optimal design alternatives on the basis of multiple criteria. Life cycle cost technique is applied to evaluate the economic performance of various types of materials and building components. Sustainability concepts are applied to design and to provide healthy, comfortable and productive buildings. Sustainability criteria are evaluated by experts in the AEC industry in North America using relative weights comparison and applying decision making techniques. This can be used as a basis for assisting designers and engineers to obtain subtle knowledge about the application of information technology in sustainable design and to pave the way for further improvement. Creating and linking such a DSS to BIM tool has the potential to aid designers design sustainable buildings and animate them easily and efficiently at the conceptual stage. Part of this integrated methodology is to develop new plug-ins within BIM tool to run the DSS by designers when selecting appropriate building components and materials based on project's requirements and attributes in addition to analyse the LCC of different design alternatives.

Numerous types of software currently used in the construction industry, such as Autodesk Revit Architecture©, Autodesk Green Building Studio© (GBS), Statistical Package for the Social Sciences (SPSS©) and Microsoft Excel©, are used in the development of the integrated model. The successful implementation of such a model represents a significant advancement in the ability to do sustainable design of a building at the early stages of its life, to optimize the selection of sustainable building components and materials through a comprehensive DSS, and to evaluate and analyse the LCC of the different design options.

8.4. Methodology

One of the main expected contributions of this proposed study is the development of an integrated model that incorporates a Decision Support System (DSS) used to help designers in selecting the best type of sustainable building components and materials and associated design families for proposed building projects based on owners' requirements. Traditionally, designers choose materials based on their known characteristics or by selecting the ones that has been used in previous projects. This practice usually creates multiple problems related to expectations, standards, and owners' budgets. The failure of this traditional method can be handled by using the MADM, which is basically based on a complex comparison between available alternatives. Therefore, the development of the proposed methodology that integrates different applications, as represented in Figure 8.1, will be implemented through the following five sequential phases:

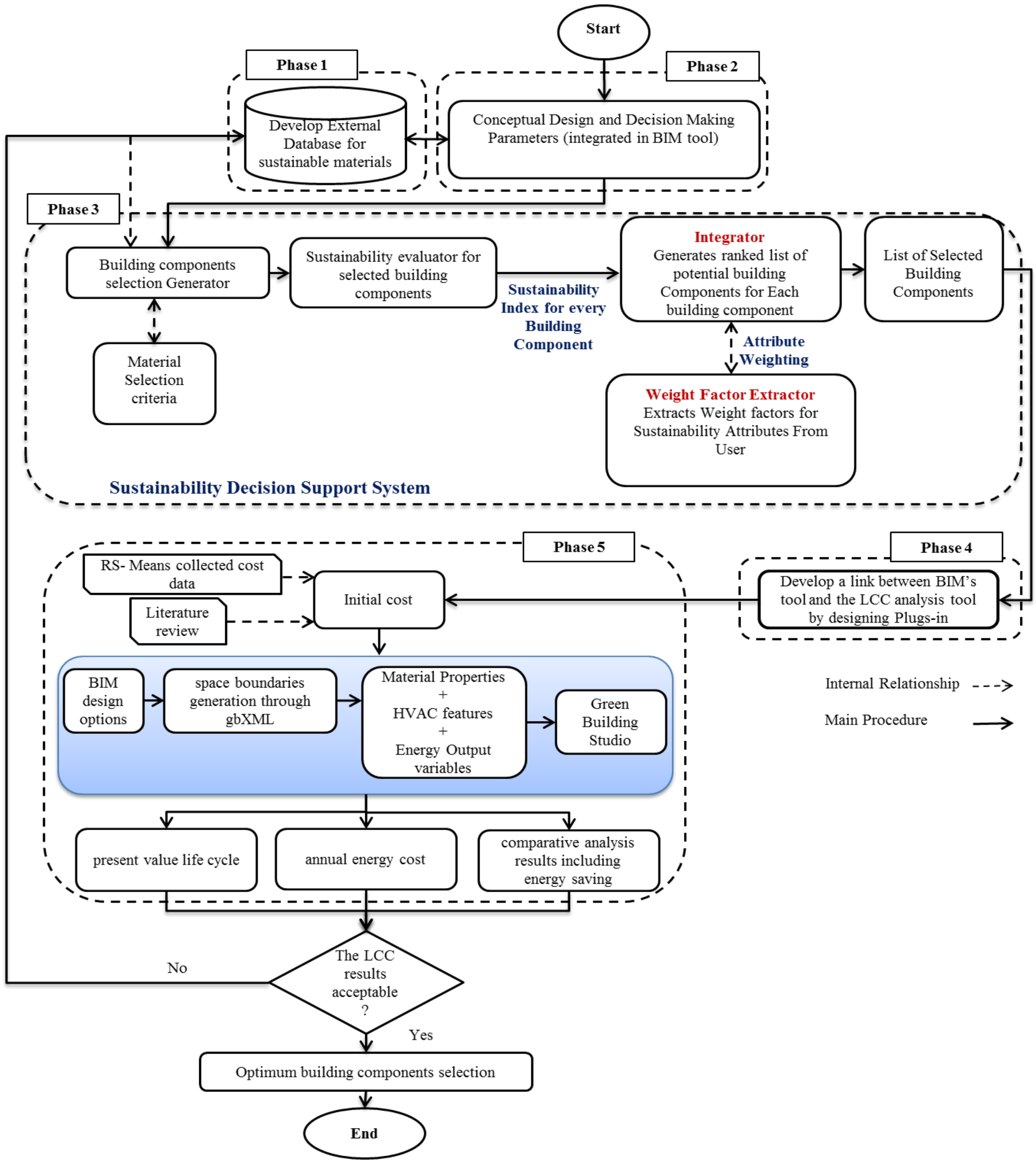

Figure 8. 1. Flowchart of the integration Process

Phase 1 consists of designing the model's relational database, which is needed while doing the design of sustainable buildings. Loucopoulos (1992) states that a consistent information system depends on the integration between databases, programming languages, and software engineering and that its life cycle incorporates the interrelated technologies of conceptual modeling and database design. The design and development of this database is accomplished in two steps starting with the conceptual modeling and ending with the physical implementation. First, problem investigation and user needs are recognized based on a comprehensive literature review. Then the database requirements are identified and the conceptual design is carried out. Second, the implementation of the data model requires that the transformation process be made from the conceptual to the logical design (Jrade and Alkass, 2007). Only afterwards the physical implementation is made by creating a list of related tables used to store the collected data based on the selected Work Breakdown Structure (WBS). The information related to green materials is stored in an external database in the form of predefined design families that can be recognized by BIM tool. The reason for developing a separate database is to have it loaded every time BIM tool (e.g., Autodesk Revit) opens, which is done by defining its path that is linked to the predefined library of BIM tool. The data related to the green materials is saved as family file format (RFA or RVT), which can be identified by the BIM tool. Thus, in the external sustainable database, up to 3,000 design families are collected from the Smart BIM library webpage, suppliers' web pages, the USGBC and CaGBC websites, as well as published data and are arranged based on the 16 divisions of the Masterformat WBS. Different types of information such as details about the materials used, suppliers' contact data, assigned keynotes, potential LEED points and assembly codes are stored in the external database.

Phase 2 focuses on customizing BIM tool to fit the modularity requirements of the model. The first step is to design and implement a 3D module capable of storing newly created families, and their associated keynotes for components commonly used in buildings by using certified green materials. The module is linked to the database developed in Phase 1. Keynotes are textual annotations that relate text strings to specific elements in the model, which are in turn linked to an external text file. It is used as an external link to the element itself with specific style and specifications. Moreover, it is very important to select a unique code for each item that is stored in a separate line in the database to ease and simplify the query and selection process.

Phase 3 consists of the developing of a DSS module, which assists in selecting sustainable building components. The DSS uses the conceptual design and decision-making parameters, along with material selection heuristics to generate a list of alternatives for each design component from the materials database. Once the set of alternatives has been generated, the weight factor extractor demands the user to enter weightings for the sustainability attributes. Alternatives in the MADM method are often defined by some attributes that are qualitative (Hwang and Yoon, 1981). For comparison purposes, qualitative attributes need to be converted into quantitative scales. This conversion usually takes place by utilizing five-point Likert-type scales (Lu et al., 2007). Although these scales convert the qualitative attributes to numbers, in many cases, these scales are not able to clearly distinguish the differences between close scores (e.g., high and very high). To solve this problem, Saaty (1980) comes up with a nine-point scale where more intervals have been employed. Values for the sustainability attributes (e.g., the importance factor of every attribute to each other) will be collected from experts in the AEC industry. Then, the user's weightings are integrated with the attribute values for each potential material and sorted to get a relative ranking of the feasible materials for each building component. The building components/products with the highest ranking are recommended by the system. The user reviews the DSS recommendation for each building component, and selects a component for each design element based on his/her professional judgment and/or the system's suggestion. While the building components are selected by the user, the DSS will do an internal check using a built in knowledge-base to detect any potential conflict between the different components and materials. The list of recommended materials for each element is modified automatically as materials are selected for the design elements.

Phase 4 focuses on creating a plug-in, which is a type of algorithm that adds functionality to BIM tool by integrating it with the energy analysis and simulation tools. *Plug-in* or *add-in* are terms used in BIM tools to signify a module containing an algorithm that makes use of the BIM tool's Application Program Interface (API). The BIM tool used in this study has a .NET API, which means that any of the .NET compliant programming languages (C#, VB.NET, F#, etc.) can be used to develop a customized plug-in. While each language has its own relative benefits, C# has been used in this study due to its simplicity, usability and powerful ability to underlay the .NET framework.

Phase 5 concentrates on the development of life cycle cost analysis module that helps in exporting the 3D design created in BIM tool using the gbXML file format. The LCC procedure starts first by calculating the initial construction costs, which evaluate the capital costs for the existing LEED®-certified buildings. The cost data used in this module is collected from RS-

Means publications. Since this study focuses only on the operational cost (energy cost), an evaluation of the total annual energy cost of the design is computed. Among the available tools that have the capability of calculating the energy consumption, energy cost and implementing LCC analysis is Autodesk Green Building Studio© (GBS), which is going to be the most relevant software for this study. The direct link between GBS and Autodesk Revit through the gbXML format makes GBS as an ideal tool to import and export the 3D design information between the different tools including the geometric data, which is needed to do all the necessary analyses. Most building energy cost comparisons can be made using the annualized energy consumption method and its associated cost and information.

In this study, the outputs extracted from GBS will be used by designers to evaluate the present value and the annual costs as well as to make comparative analysis of the energy savings and emissions reductions. This will help designers evaluate different design alternatives from their initial and operating costs perspectives. The target is to compute and compare the operating cost of these alternatives and to determine the most economical one over the project's life cycle.

8.5. Selection and characterization of the TOPSIS method

The unique characteristics of the TOPSIS method make it an ideal choice to solve the material selection problems. In TOPSIS, a vast range of materials' features and all their performance attributes are involved. To implement and use TOPSIS during the material selection process, the main impact of each potential factor that influence that process should be considered with respect to the other factors.

In TOPSIS, the results can be ranked according to their preferences and their numerical values. This ranking gives a clear comprehension of the differences in the preferential alternatives and their similarities, whereas other MADM methods (e.g., ELECTRE) show only the ranking values of the alternatives regardless of their differences and similarities. While working with vast numbers of alternatives and attributes, TOPSIS is more efficient and faster.

The principal objective in TOPSIS is to select the best alternative with the shortest distance from the ideal one (Yoon, 1981). To achieve this goal, we have to find the farthest distance from the negative ideal solution and the closest to the positive ideal solution. The unique features of TOPSIS explains its popularity and efficiency where the vector normalization eliminates the units of criterion function so any change in one attribute can be presented in a direct or opposite behavior by the other factors.

Shanian et al. (2006) thought that in an MADM problem, it is important to know the relative significance of each criterion. As a common approach, the weights are presented in a normalized set in which their total sum equals to one. Meng (1989) considered that Entropy is the measurement of the disorder degree in a system that can also be an indicator that shows the effective information provided by the data. The entropy method can be used not only to quantitatively estimate the data, but also to objectively calculate the relative weight of information (Shannon, 1948). If entropy values are lower, the numerator degrees are more proportional, implying as close to perfect entropy as possible. Conversely, if entropy values are higher, the numerator degrees have a more irregular inflection. Therefore, entropy weight method was introduced to obtain the relative weight of each attribute (Qiu, 2002). Each attribute is assigned a measured value to calculate the entropy values. The entropy values for each criterion are then compared, and the relative significance levels of each other are calculated (i.e., the relative weight). Next, the entropy weight is obtained based on the appraisal matrix information.

Pratyush and Jian-Bo (1998) believed that Entropy method is a technique used to evaluate the amount of uncertainty that is represented by a precise probability distribution. Furthermore, Huang (2008) agreed that a broader distribution shows a highest level of uncertainty than does a sharply packed one. Applying the entropy method requires the following two steps:

(1) Step one, Normalization of values

The Entropy method applies a different procedure to normalize the values. Accordingly, it divides the value of each element (r_{ij}) of the weight matrix by the sum of the all elements' values ($\sum_{i=1}^{m} r_{ij}$) to calculate the normalized values of the weight matrix' elements, p_{ij} using the equation [8.1].

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \quad j = 1,2,\ldots,m \qquad [8.1]$$

(2) Step two, Calculation of the entropy for the criterion

To calculate the entropy values (E_j), equation [8.2] is employed where k=$\frac{1}{Ln\,(m)}$, (m) is the numbers of criteria, and (p_{ij}) is the normalized values of the weight matrix elements.

$$E_j = -k\ \sum_{i=1}^{m}\left[p_{ij}\ln\left(p_{ij}\right)\right] \quad j = 1,2,\dots,J; \;\; i = 1,2,\dots,I \qquad [8.2]$$

One of the entropy method's benefits is the possibility to mix the decision priorities with the sensitivity analysis. Thus, the final weight is the combination of both them. If the criterion's priorities are similar to the decision-maker's ones then the set of weights can be calculated by using equation [8.3], where d_j equals$1 - E_j$. In this equation it is considered that all the criteria have the same priority.

$$w_j' = \frac{d_j}{\sum_{j=1}^{n} d_j}\ ,\forall_j\ , \quad d_j = 1 - E_j\ , j = 1,2,\dots,J \qquad [8.3]$$

In the case of applying priority based on the project limitations, previous experience or any particular constraint of design, the weights are calculated by using a factor known as λ, which stands for the arranged order of increasing importance of the non-normalized subjective weights. After arranging the assigned weights, the sum of the normalized subjective weights (λ_j) should equal to hundred. The prioritized weights (w_j') can then be calculated using equation [8.4] in which w_j' is the Entropy weights without considering any priority.

$$w_j' = \frac{\lambda_j w_j'}{\sum_{j=1}^{n} \lambda_j w_j'} \quad , \quad \sum_{i=1}^{n} \lambda_j = 100 \qquad [8.4]$$

The database module includes assessment of suppliers' materials and their BIM information. The information stored in this database is organized based on the main suppliers of the different building components including doors, roofs, windows, ceilings, floors and walls. Next, the important sustainability factors are identified from the literature review. Afterwards, the DSS is designed based on the applied decision-making approaches that involve TOPSIS and Entropy, which are used to choose the optimal alternative. Then, by connecting the database with the DSS, an integration interface is developed into BIM tool (i.e., Autodesk Revit).

Figure 8.2 presents the model's architecture. The data preparation consists of generating alternatives by assessing and reviewing suppliers' materials and their BIM families that are collected and stored in the database, and organizing the sustainability criteria that have the highest influence on construction projects. In the BIM-integrated DSS development procedure, selected criteria will be converted to dimensionless weights by employing Entropy methods. Criterion weights are organized in a matrix form. To create the decision-makers matrix object oriented programming language, in this case C#, is used to program the DSS, which is integrated with BIM tool (i.e., Revit). Both matrices are imported into the background of Revit in the form of plug-in to run TOPSIS procedures. Finally, the optimal sustainable alternative is presented by the integrated DSS in BIM tool. The developed DSS is based on the multi-criteria assessment weighting scale technique combined with Entropy, which enables comparison and ranking of different alternatives and scenarios. The other method employed in this DSS, is the TOPSIS Logic which is mixed with a weighted criteria matrix to show the shortest distance from positive ideal solution and the longest distance from the negative ideal solution.

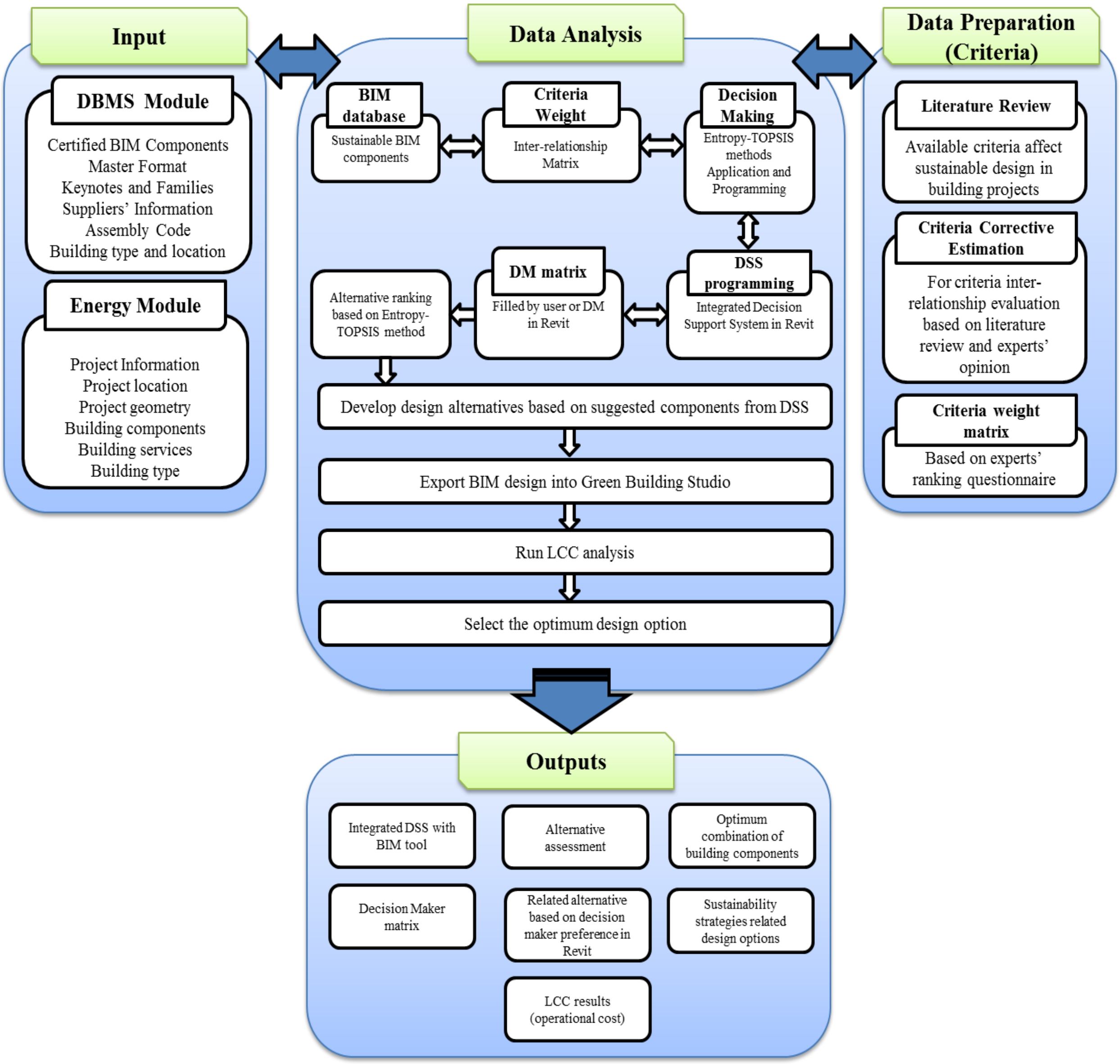

Figure 8. 2. Model's Architecture

Figure 8.3 shows the main components of the proposed DSS. It contains (1) Materials and building components available in the construction industry, (2) Project character (i.e. project orientation) as well as sustainability attributes selected by the experts, (3) Owners/decision-makers' fulfilment goals toward material selection based on their priorities such as time, energy consumption, total cost, life cycle cost, and positive social image of the building by meeting and supporting sustainability criteria.

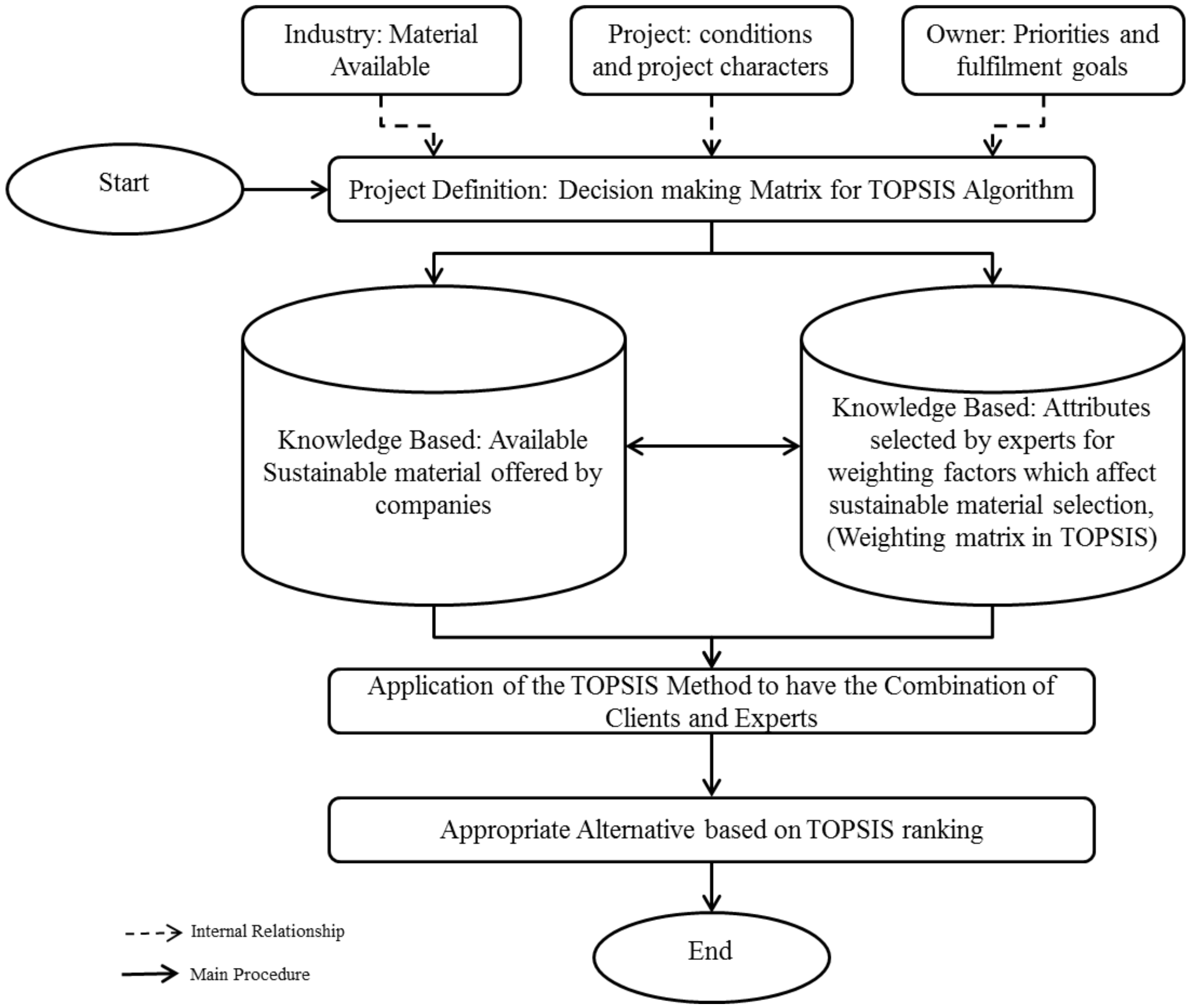

Figure 8. 3. Decision Support System Schema using TOPSIS algorithm

The most critical part in this study is the selection and arrangement of the criteria and attributes that affect the selection of sustainable materials for building projects. Basically, the assessment of the attributes is made based on the intense literature review, previous research work and survey completed by experts (information is collected from five sustainable construction material specialists and 25 sustainable design consultants). In this survey, the experts are asked to choose the criteria with the highest significance in sustainability of the building projects. The criteria for sustainability are divided into three categories: 1) environmental, 2) economical, and 3) social criteria. Each of those categories includes sub-criteria that have been listed in the scoring system completed by experts. Table 8.1 shows the sustainability assessment criteria and sub-criteria.

Table 8. 1. Sustainability assessment criteria used for DSS

Main category	Criteria	Sub Criteria
Environmental criteria	Environmental Impacts (EI)	Global Warming Potential Ozone Depletion Potential Acidification Potential Eutrophication Potential Smog Potential HH Respiratory Effects Potential Weighted Resource
	Energy & Atmosphere	Operational energy as Lighting and power, cooling and heating, Minimum Energy Performance, Embodied energy as mining, manufacturing, on site process, transportation and final disposal, Onsite renewable Energy, Energy consumption during building life
	Material & Resources	The application of renewable material, Recycled content
Economical factor (cost efficiency)	Cost	Costs of resources and materials, Labor costs, Operation & Maintenance costs, Renovation and destruction costs
	Investment criteria	The speed of return on investment, Initial investment, Exchange amount
	Time	Approximated Construction time
	Construction issues	Constructability, Flexibility, Material and equipment availability
Social wellbeing	Indoor Environmental Quality (Health of occupants)	Indoor environment comfort, Low-Emitting Materials: Adhesives and Sealants, Low-Emitting Materials: Paints and Coatings, Low-Emitting Materials: Flooring Systems, Low-Emitting Materials: Composite Wood and Agrifiber products, Controllability of System: Lighting & Thermal Comfort
	Design and architecture issues	Daylight and Views, Productivity, Individualization and social identity, Physical space and performance, Aesthetics and architectural issues

Weighting Matrix Applied in the TOPSIS method, validated by experts is stored in the DSS, which will be integrated into BIM tool (Autodesk Revit) by developing a plug-in. By implementing the DSS plug-in, designer (Decision Maker) needs to fill the decision-making matrix, then the inputted data is processed in the background to run the next steps, which include TOPSIS logic. The final results will be presented as a descending-order ranking of the alternatives. Consequently, the highest rank belongs to the most appropriate alternative (the most proper material from the list of companies).

8.6. Model Implementation & Validation

Portion of the technical knowledge required in the development of the integrated model is obtained from an intense review of the literature and by consulting experts who have wide experience in sustainability and decision-making approaches. Next is identifying the Criteria/attributes and accordingly calculating the Weight Matrix using the Entropy method to establish the Decision Maker's Matrix. The next phase is normalizing the decision-making Matrix (DMM) made by the Decision Maker and then multiplying the DMM by the Weight Matrices to get the weighted decision-making matrix in order to evaluate the Positive Ideal and Negative non-Ideal Solution and finally to calculate the shortest distance from the Positive Ideal Solution (PIS), farthest distance from the Negative non-Ideal Solution (NIS) and the relative closeness to the ideal solution for each alternative. After that, is ranking the alternatives based on their proportion of relative closeness. The data set required for the development of the model is divided into two categories: (1) materials and components alternatives (data source is: vendors of basic assembly groups including doors, walls, windows, ceilings, roofs and floor that are made of sustainable materials) and their correspondent BIM families, (2) green building sustainability controlling criteria.

In order to define alternatives, information from the SmartBIM library website is collected and assessed. The SmartBIM Library is a web-based collection of predefined design families, which incorporate detailed information that can be integrated into the design workflow. Due to the big number of companies/factories that produce/supply building products, which are currently available in the market, only leading companies/factories with wider ranges of products have been selected. To ease the process of accessing the required data, the selected companies and their materials' BIM information are hyperlinked to the list of products in the developed plug-in. In order to obtain the weight criteria's matrix from the selected criteria as an output, the experts' opinions have been utilized. In order to prepare it, a blank weight criteria matrix as shown in Figure 8.4 has been handed to the experts for scoring purposes. The weight criteria matrix is sent to 28 selected experts and practitioners. Only 25 responses are received, 5 of them are from sustainable construction material specialists and the remaining 20 are from practitioners. Figure

8.4 shows the matrix sent to participants and the relevant information generated by responses, which include respondents' age distribution, education and sustainability knowledge.

Dear Responder,

Thank you for accepting to participate in our survey " Building Projects Sustainable Criteria Evaluation Test".

This questionnaire is assessed to evaluate the inter-relationship between sustainability factors in building projects by expert point of views. In this questionnaire, you will asked to give values to the criteria relationship according to Saaty's 9 point scale.

This questionnaire has been made available as part of research by Farzad Jalaei and Dr. Ahmad Jrade from Department of Civil Engineering, University of Ottawa.

At the end of the questionnaire, background information will be asked. The questions are optional, but those will help our research.

Help	Inter-relationship Matrix	Environmental Impacts	Energy and Atmosphere	Material and Resources	Cost	Investment Criteria	Time	Construction Issues	Indoor Environmental Quality	Design & Architecture
Saaty's 9 point Scale	Environmental Impacts	1.00								
Scale1=Equally Important	Energy And Atmosphere		1.00							
Scale3=Weakly Important	Material And Resources			1.00						
Scale5=Strongly Important	Cost				1.00					
Scale7=Very Strongly Important	Investment Criteria					1.00				
Scale9=Extremely Important	Time						1.00			
	Construction Issues							1.00		
	Indoor Environmental Quality								1.00	
	Design & Architecture									1.00

Background Information:

1) Age:
2) Educational Degree: Graduate Diploma__ Bachelors__ Msters__ PhD
3) How many projects have you had with sustainability analysis requirement?
4) Have you had experience in Decision Making approaches? Yes__ No__

Figure 8. 4. Study Criteria Weight Matrix Scheme

To merge all the collected responses into one matrix, a normality behavior test for the responses of each question has been run by using the Statistical Package for the Social Sciences (SPSS©) software's normality analyzing tools. The obtained results it is found that all the responses had normal distributions. Therefore, for each correlative score, the normal distribution's average is substituted. Table 8.2 shows the un-weighted criteria matrix organized based on the experts' opinions.

Table 8. 2. Un-weighted Criteria matrix assembled by experts' opinions

	Environmental Impacts	Energy And Atmosphere	Material And Resources	Cost	Investment Criteria	Time	Construction Issues	Indoor Environmental Quality	Design & Architecture
Environmental Impacts	1.00	0.14	0.11	5.00	3.00	3.00	3.00	5.00	1.00
Energy And Atmosphere	7.00	1.00	0.17	6.00	5.00	1.00	1.00	7.00	1.00
Material And Resources	9.00	6.00	1.00	9.00	9.00	9.00	9.00	5.00	7.00
Cost	0.20	0.17	0.11	1.00	7.00	1.00	0.17	0.17	0.14
Investment Criteria	0.33	0.20	0.11	0.14	1.00	0.17	0.17	0.20	0.14
Time	0.33	1.00	0.11	1.00	6.00	1.00	7.00	1.00	1.00
Construction Issues	0.33	1.00	0.11	6.00	6.00	0.14	1.00	1.00	3.00
Indoor Environmental Quality	0.20	0.14	0.20	6.00	5.00	1.00	1.00	1.00	0.20
Design & Architecture	1.00	1.00	0.14	7.00	7.00	1.00	0.33	5.00	1.00

To convert the un-weighted matrix to a weighted one, the Entropy weighting approach has been employed. First, the matrix is normalized. Second, the entropy of the weights is calculated. Third, the (d_j) factor is estimated. Finally, the weighted criteria are determined by taking the ratio between each dj and the summation of dj(s) as represented in table 8.3.

Table 8. 3. Weighted Entropy matrix

	Environmental Impacts	Energy And Atmosphere	Material And Resources	Cost	Investment Criteria	Time	Construction Issues	Indoor Environmental Quality	Design & Architecture
Environmental Impacts	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy And Atmosphere	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Material And Resources	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00
Cost	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00
Investment Criteria	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
Time	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.00
Construction Issues	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00
Indoor Environmental Quality	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00
Design & Architecture	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13

Part of designing and developing the DSS is to write an algorithm in the form of a plug-in in BIM tool, in this case Autodesk Revit. This plug-in enables users/decision-makers to evaluate the selected materials based on their sustainability features while doing the conceptual design of proposed buildings. The plug-in is programmed using C# the object oriented programming language, and is imported into the toolbar of Autodesk Revit as a shortcut. Figure 8.5 presents the developed plug-in imported into Revit's toolbar. TOPSIS, once run, begins its procedures by employing two matrices: the criteria weighted matrix and decision makers matrix. The developed plug-in helps users import weights into the decision-makers matrix, which are recognized by the user's comparison results, based on the available products in the external database of BIM tool. The criteria matrix is coded and inserted in the background of the plug-in's program. As shown in figure 8.5, by using the plug-in, decision makers can compare and score the alternatives of different assembly groups.

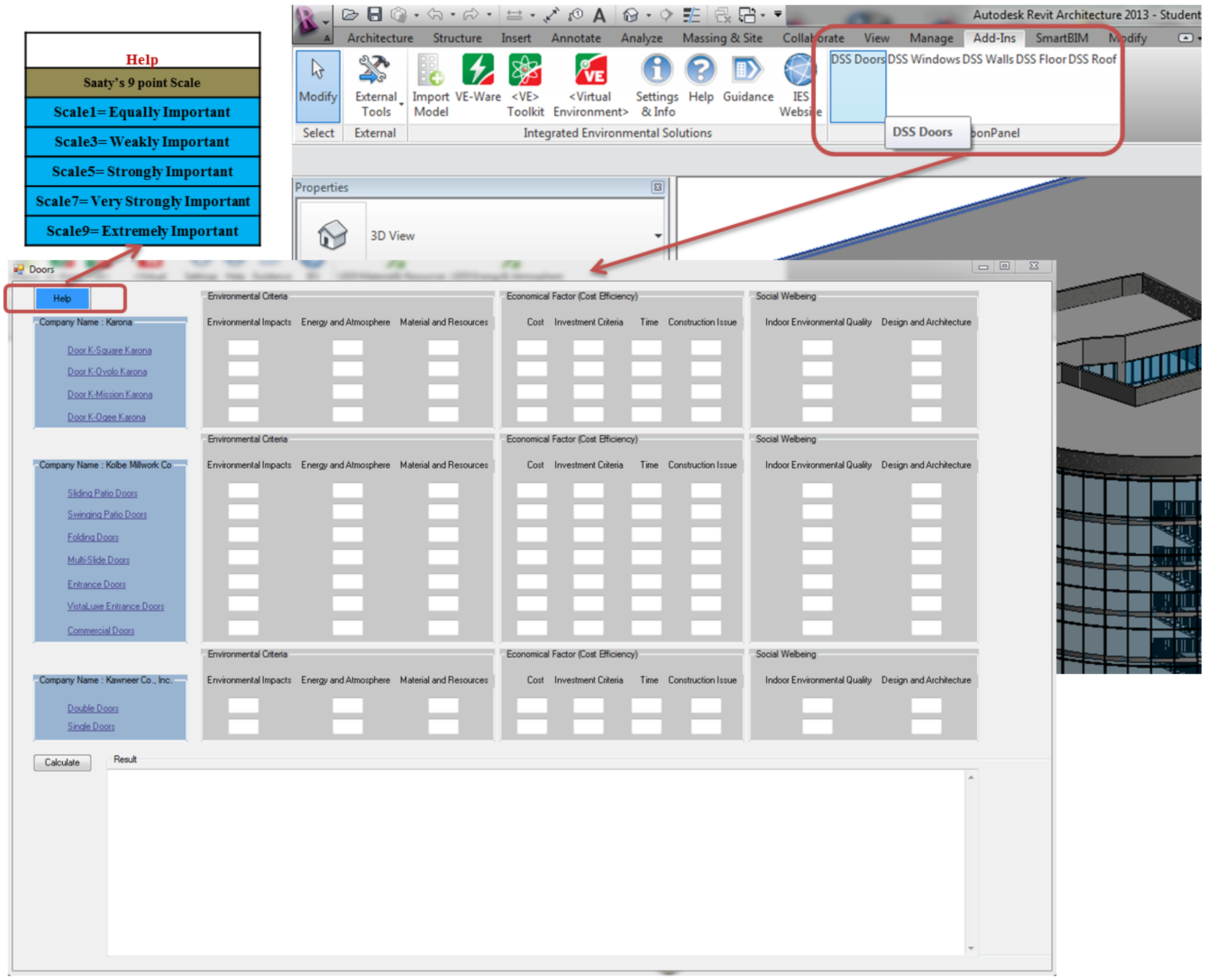

Figure 8. 5. Snapshot of DSS plug-in developed in Autodesk Revit

To validate the developed model, its performance is examined through the use of an actual five floor office building project that can house around 300 people (occupants), which is currently under design in the city of Ottawa. The proposed construction site has a total area of 46,980 ft^2 and the building's gross area is 88,587 ft^2. Building functions are distributed into three categories: public, semi-public and private. Public function is related to both ordinary people and employees such as conference and exhibition rooms. Semi-public spaces include secretary offices and managers' rooms, which are used by employees and visitors. Employees' offices and private gathering rooms are considered as private spaces used by employees and managers. In order to control the sunlight, louver systems are installed to improve indoor daylighting to limit glare and redirect diffuse light. The authors created a 3D conceptual design of the current project where its associated sustainable components and materials are selected from the developed database. The components used in the design of this case project have their specifications as it is recommended by the DSS plug-in. Every component, such as floor, wall, roof, and window has its associated sustainability information linked to the families inherited into BIM tool, which includes the manufacturers' web pages and contact information. Figure 8.6 shows a rendered snapshot of the sustainable office building, which is created by using the developed model.

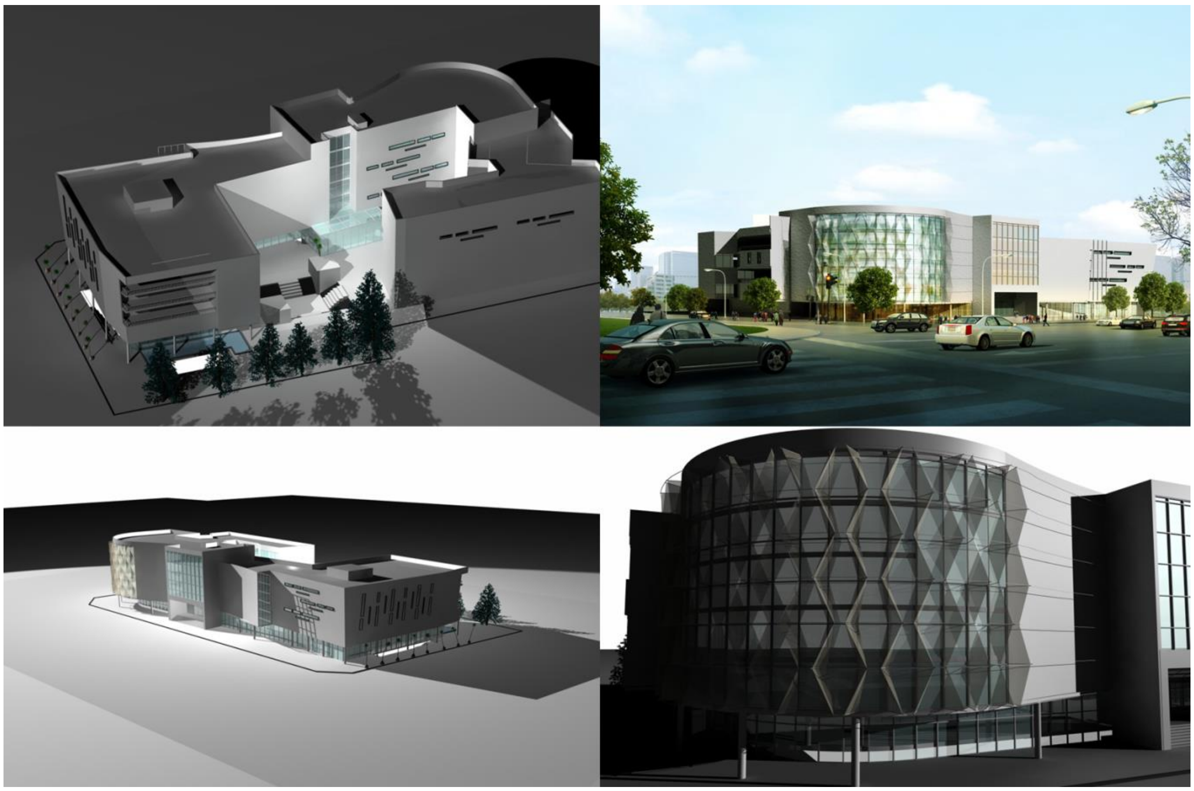

Figure 8. 6. Snapshot of the sustainable case building model (Office Building)

The designer needs to select and decide on the sustainable materials and components provided by different suppliers' to create alternatives for the current building including doors, roofs, ceilings, walls, windows and floors. To use the developed DSS, the designer must use TOPSIS plug-in loaded in the toolbar of Autodesk Revit. After running the plug-in, the decision maker is asked to create the decision-maker matrix by scoring the alternatives based on the defined criteria. Every product is linked to its Producer website or SmartBIM library webpage that provides the user with all the required technical specifications of that product. The help button in the plug-in provides the user with information on how to fill the blank spaces in the form based on the nine-point ranking scale.

To get the results, the user is required to click on the calculate button included in the tool bar designed in the DSS. The final results will be presented as a ranked list of alternatives and their associated producer names, as well as the (EI_i) factor. For instance, the snapshot of the filled DM matrix and the final sorting of the alternatives for the door component is shown in figure 8.7.

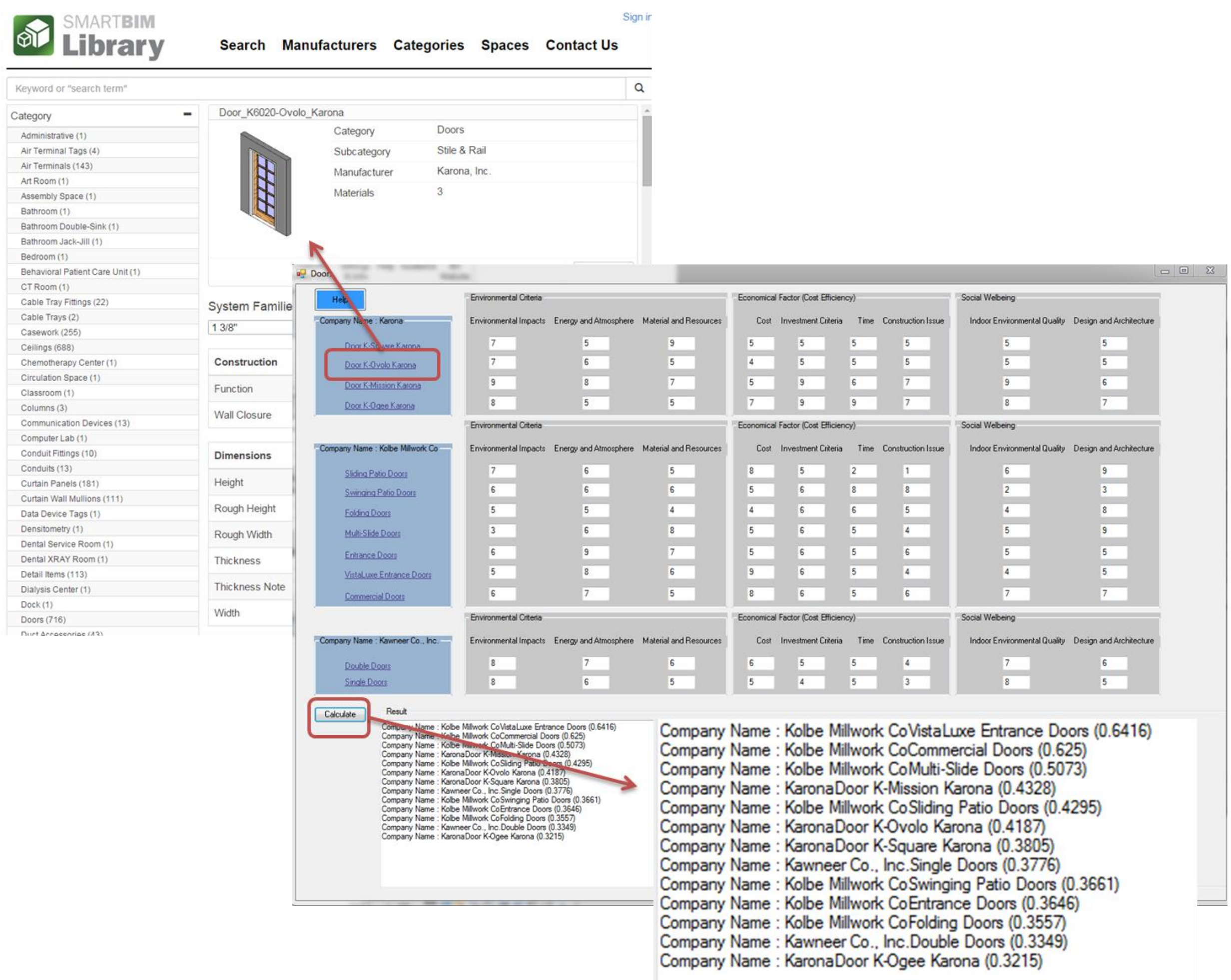

Figure 8. 7. The snapshot of filled form in the DSS and the results for door component

To apply the LCC analysis method, the authors created two conceptual design options of the current project where its associated sustainable components and materials were selected based on the first two alternatives recommended by DSS (for instance, Kolbe Millwork Co Vista Luxe Entrance Doors and Kolbe Millwork CoCommercial Doors) for every building component. In order to have an accurate energy analysis of the building case project, the created 3D geometric model must be converted into an analytical model. First, all the spaces are converted into rooms.

In BIM tool, rooms are considered to be equivalent to zones that need to be defined. A thermal zone is a completely enclosed space bounded by its floors, walls and roof and it is the basic unit for which the heat loads are calculated. The extent of a “room” is defined by its bounding elements such as walls, floors and roofs. Once a “room” is defined for the purpose of analyzing the building’s energy, these bounding elements are converted into 2D surfaces representing their actual geometry. However, overhangs, which do not have a room, are considered to be shading surfaces. In order to determine whether a room is an interior or an exterior one it is important to define it’s adjacent in the analytical model. By using the GBS plug-in in BIM tool, designers will directly transfer the created model of the building to GBS via the gbXML formats.

The results of the base run analysis are illustrated in figure 8.8, where the annual energy cost and life cycle cost for the 1st design option are $114,838 and $1,564,094 respectively, while those for the 2nd design option are $139,103 and $1,894,588 in the same order. Other information such as annual CO_2 emission, annual energy and life cycle energy are provided in the base run as well. Figure 8.9 provides graphical representations of the information related to the monthly cost of the total energy, electricity and fuel (natural gas) for each of the two design options. A careful evaluation and comparison of the cost data presented in the graph show that the total energy cost of the 1st design option is on average around $2,000 less than the 2nd option for every month. The average electricity cost for the 1st option shows a drop of around $1,000/month if compared with the 2nd one, while option 2 has around $1,000/month more than option 1 in the cost of fuel (natural gas). Comparing the results shown in Figure 8.8 and figure 8.9, the first design option recommended by the developed DSS can be considered as the optimized alternative.

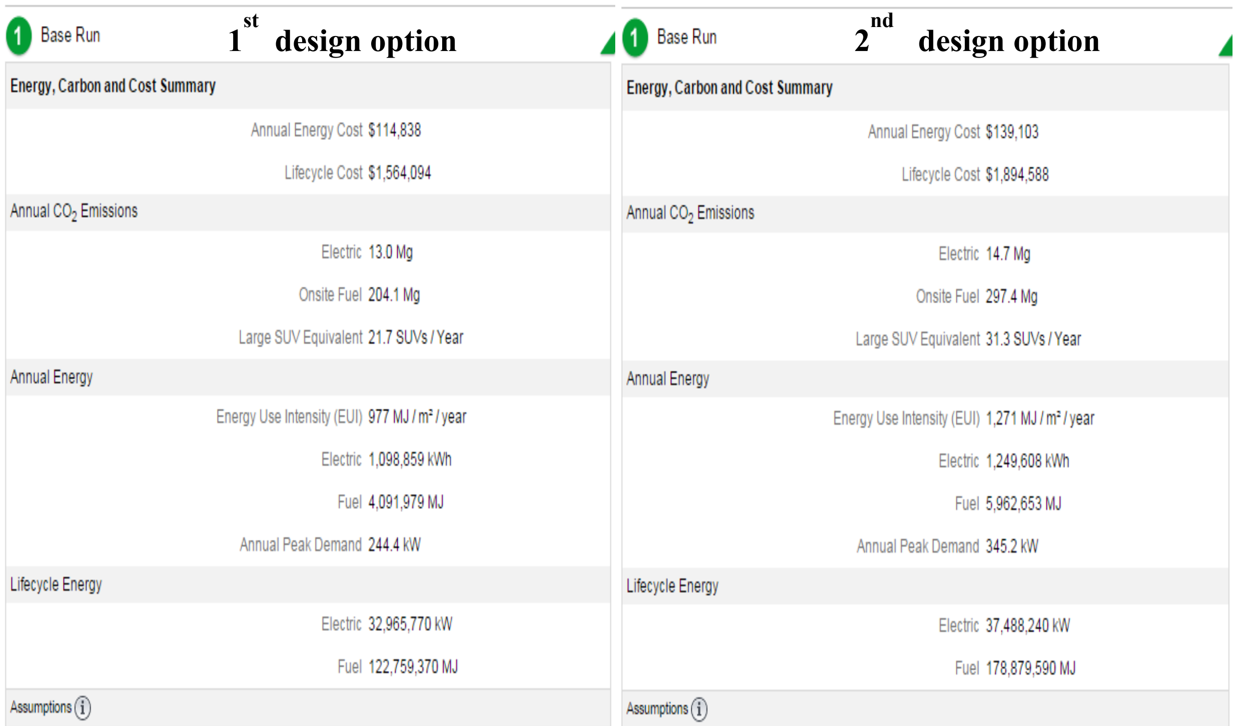

Figure 8. 8. The base run analysis results in GBS for two design alternatives

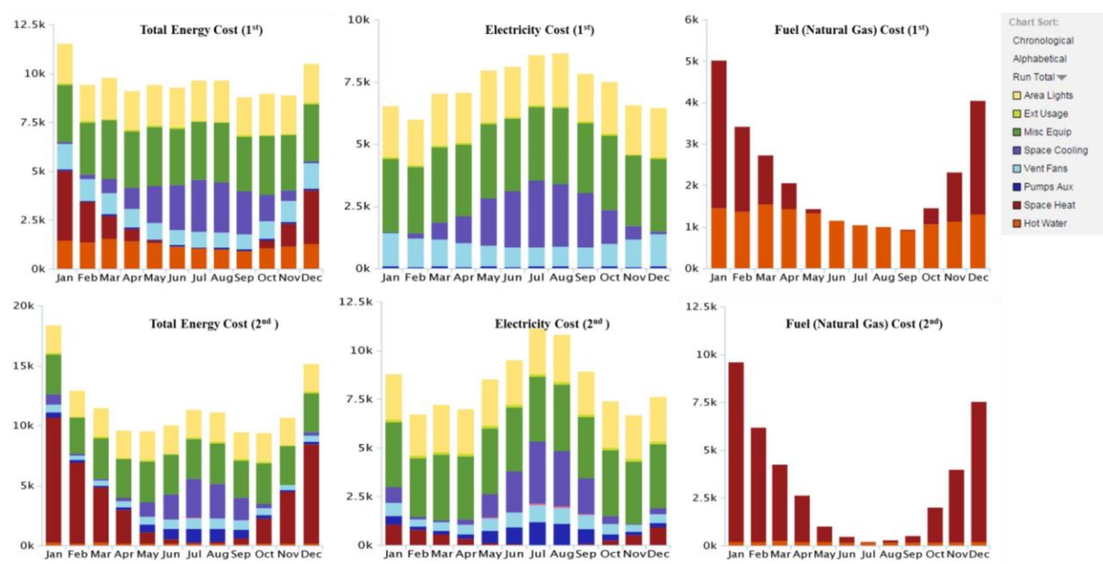

Figure 8. 9. Monthly cost analysis results for Total Energy, Electricity and Fuel (Natural Gas) for two design options

8.7. Conclusion

This study aimed to investigate the feasibility of integrating BIM, DSS and LCC. An efficient framework for this integration is created and developed that takes into consideration the sustainable design requirements and the functionality of the BIM tool. The intent of this study is to help decision makers take important decisions related to the continuation or dismissal of proposed buildings at the conceptual stage. The novelty highlighted in this paper describes the development of an integrated model that includes a Decision Support System (DSS) used by designers to decide on and select the optimum type of sustainable building components for proposed projects based on owners' priorities and sustainability criteria. The developed DSS is integrated into BIM tool through an automated process by creating new plug-ins so that users start doing design of a proposed sustainable building at the conceptual stage in a timely and efficient way. Using a BIM-LCC integrated platform moves the design decisions forward at the early stage especially when comparing different design alternatives, which is considered to be an attribute of this research.

The case project used in the validation section of the manuscript was in its very early design stage. Since its design was not completed yet, authors received brief information about the project from the owners and their consultants. Based on the provided information, the authors created a Revit model of that project and accordingly applied the developed method that its analysis results were discussed with the project team for feedback. During that discussion, the DSS generated in the BIM model were suggested to the design team to be considered for the case project. It was proven that in case of using the recommended products for every building component, the developed design option shows around 17% benefit on energy cost as well as on its life cycle cost, which can be considered as the optimal alternative and a validation for the developed DSS. Applying a comparative LCC analysis between different design alternatives is considered as a benchmarking practice that is offered to the design team to give them a proper feedback on making decision related to the materials selection and in case of any changes to the design and/or materials selection, the LCC results will be changed.

It worth to mention that the focus of this manuscript is the conceptual design stage where the design is at its earliest stage and accordingly as it changes the costs will change, therefore an accurate estimate of the costs for proposed projects is not achieved at the conceptual stage where the margin of errors is high and the level of accuracy is low. Since every case project has its own sustainability specifications, a detailed comparison of the results between them is not helpful for validating the developed model. The main idea behind validating the developed model is to test its workability, dependency and accurate outcomes to help designers make constructive decisions during the conceptual design stage of project's life.

The integrated model is user-friendly, efficient and easy to use. As it is validated, the combination of building components proposed by the DSS, represent a minimum LCC values when compared with the other suggested combination. Although this is an ongoing research, its potential for more development is proven to be possible. The DSS database is on a small scale, but it can definitely be expanded to Online Analytical Processing (OLAP) design in order to enable relevant green material producers to update their information online periodically.

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CHAPTER 9

SUMMARY AND CONCLUDING REMARKS

9.1. Summary and research contribution

The intent of this thesis is to help design team generate a better idea about the project while making important decisions related to the continuation or dismissal of that project at the conceptual stage. Though the level of accuracy of the available information at that stage is low, nevertheless decisions have to be made. Thus, any additional information would be an asset and helpful to support the decision. The novelty highlighted in this thesis describes the model's different modules, which are integrated into each other based on an automated process by creating new plug-ins and improving the functionality of the existing ones so that users will be able to start the sustainable design of a proposed building project at the conceptual stage of its life in a timely and cost-effective way. Using a BIM integrated platform moves the design decisions forward at the early stage especially when comparing different design alternatives, which is considered to be an attribute of this research. In this thesis, a methodology was developed to integrate BIM and sustainable design through five main modules as the main components of the described model.

The integration requirements are based on the literature review described in chapters two and three. The integration involves data collection from different sources. These include drawings, sustainability specifications, general conditions, bills of quantity, environmental impact specifications, and life cycle cost of building projects.

The integrated model will have the following characteristics:

- Information intensive; it incorporates different data from various suppliers to store and use the available data in an attempt to improve the practicality of doing sustainable design.
- Efficient; it automates the export and import process between BIM and several tools to provide a user friendly environment for designers to evaluate different aspects of the sustainable design through an integrated model.

- Flexible; it allows data additions and modifications to enhance the historical data in a user-friendly mode.
- Practical; it includes procedures that execute fast calculations by applying available tools (expressions, equations, and programming).
- Automatic; it helps users in selecting the best sustainable materials and components that suit the set budget and the appropriate design that has a contiguous specification similar to the forecasted one.

This research is presented as a paper based Ph.D. thesis, the development and validation chapter of this thesis is represented in the format of journal papers. Every journal paper is focused on one or two main modules introduced in the methodology. Three of these papers have already been published and the remaining two are submitted for publication in the near future.

9.2. Research Contribution

The contributions of this research reside in the following:

1. Developing a unique approach to do sustainable design by integrating the functionalities of BIM tools. The integration is demonstrated by looking at the most significant aspects of sustainable design (five modules) including the most popular green building rating system (LEED) and the most common and prevailing BIM software (Autodesk Revit).
2. Designing an external database to store information about sustainable building materials and components commonly used in North America and their sustainability principles and costs. The data related to the green materials is saved as design family files (RFA) or Revit files (RVT), which can be identified by the BIM tool. Thus, the external database contains design families collected from the literature, suppliers' web pages, USGBC and CaGBC websites as well as published data, arranged based on CSI masterformat. Different types of information such as details about the materials used, suppliers' contact data, assigned keynotes, potential LEED points and associated costs are stored in the external database.
3. Developing an integrated model that incorporates a Decision Support System (DSS) used to help designers in selecting the best type of sustainable building components and materials and associated design families for proposed building projects based on owners' requirements. Traditionally, designers choose materials based on their known characteristics or by selecting the ones that has been used in previous projects. This practice usually creates multiple

problems related to expectations, standards, and owners' budgets. The failure of this traditional method can be handled by using the MADM method, which is basically based on a complex comparison between available alternatives. Creating and linking such a DSS to BIM tool by developing new plug-ins has the potential to aid designers design and animate sustainable buildings easily and efficiently at the conceptual stage.

4. Calculating the transportation embodied energy through the development of a plug-in in the BIM tool based on the algorithm described in Chapters 4 and 7. The algorithm receives the weight of every building component from the user and implements the truck selection procedure. Then, the distance between the location (origin) of the materials' suppliers and the location of the project (destination) is automatically calculated once the required postal codes are entered by the user. When the required data (i.e. weight of the material, postal codes of origin and destination) is entered, the plug-in calculates the transportation energy of every building component as well as the number of trucks and their types.
5. Incorporating the development of a computer model that automates the process of identifying the required number of points that must be accumulated and estimating the cost of certification based on LEED Canada certification categories. The developed model will help the design team in analyzing how different designs meet LEED credits. Furthermore, the proposed model provides a general idea of the cost of this specific certification.

The model is simple and user-friendly where user inputs and error prediction are minimized. Time reduction, fast calculations, and professional output reports are some of its advantages.The successful implementation of this methodology helps the project team make an effective decision when selecting sustainable design strategy and using building performance simulation to evaluate the sustainability performance of a building during the conceptual stage and evaluate the EI, Energy analysis and lighting simulation results for the whole building and the embodied energy of every building component and to list its earned certification points and associated costs. To be able to use this integrated BIM model in the industry scale, it is required to hire experts and professional programmers especially for database development, updates and maintenance. Enhance the capability of storing and transferring more data from materials quantity take-offs of Revit within gbXML and IFC needs time and cost efforts. All these costs should be considered in the cost of implementing such a system.

9.3. Limitations of the Developed Model

It must be emphasized that the developed model can only be used to prepare sustainable design and accordingly generates sustainability related information for building projects that are 1) commercial, 2) Residential and 3) institutional. The design team maynot utilize the developed model to prepare Energy, LCA, LCC, LEED and cost information for other type of projects (i.e. infrastructure projects).

Listed below are the model's specific limitations:

- One of the most important limitation of this research is that the developed model and application have never been fully validated in real sustainable projects. Every module is separately applied and tested on case projects, which are represented in the technical journal papers, but the whole automated model is applied in a real building project and the results should be validated. This is also the next step needed to make the results of this research truly helpful to professionals in the construction industry.
- The proposed model cannot be applied at the detailed design stage of a building project because its integrated database stores information only for components that are commonly used in building projects. Furthermore, the developed database has been designed based on collected data, which are supported by Revit that contain limited number of certified components, all of that are designed and provided by their manufacturer. This is a limitation for the model because it does not cover all the existing sustainable building components. This means that there are several green families that should be added to the database.
- Missing information during the transformation process from the BIM tool to the other tools (i.e., energy analysis and simulation) includes the information required as input by different software. Some information needs to be entered manually by the user after the transferring process, while other types of information are automatically assumed by the software itself (i.e. information about the type of materials when transferring from Revit to Ecotect or IES-VE).
- This study looked only at the integration between BIM and sustainability through the application of only two credits (i.e. MR and EA) of LEED-NC rating system. The results thus were limited to LEED instead of the general framework of sustainability. Plus, all

the software applications developed in this research were quite generic. More intensive coding will be desirable to turn the results of this study into actual products. Finally, considering the immaturity of BIM and LEED integration, technical issues were dominant in this research. Nevertheless, in an actual LEED project, the cost-benefit implication of such integration is equally important to determine the best strategy to leverage the certification process using BIM.

- Limitation in support for direct data Input/ Output through the ODBC driver is hindering the development of more flexible and creative strategies of information exchange between project team members. The openness of the software's APIs also needs to be addressed. Due to the unique circumstances of a project, software users want flexibility to customize the application to better serve their needs in manipulating the model information.
- The number of experts who participated in the survey was limited. To evaluate the sustainability criteria in a more efficient and accurate way, it is required to increase the number of experts with wide variety of backgrounds in sustainable design.

9.4. Recommendations for Future Research

This research can be expanded as follows:

- By incorporating virtual design and construction systems into practice. The future expansion of this research can focus on using analysis and visualization tools to support the decision making process for sustainable building components at the conceptual stages, through design, construction, and its operational life.
- Integrating analysis and visualization tools such as BIM, Geographical Information Systems (GIS), LCA, Energy analysis and lighting simulation, LEED and LCC provides an effective way to evaluate and visualize building lifecycle processes that occur inside and outside the buildings. These abovementioned processes can be applied in two interrelated areas: (1) Developing high performance green buildings, and (2) Conducting interdisciplinary research and utilizing multiple data sources.
- Reducing the lack of interoperability between the various disciplines involved in a building project by using semantic interoperability and ontologies for information exchange throughout the building's life-cycle.

- By considering people, technologies, and processes as three key elements of interdisciplinary research in building science, research plans can be centered on the technological aspects of the buildings (i.e. technology and process), however, the objective is to enable users to engage actively in collecting vital information and facility management decision making.
- Provide a comprehensive, accurate and easy-to-use way for people to view the potential gains in terms of energy consumption and environmental impacts of their sustainable building.

CHAPTER 10

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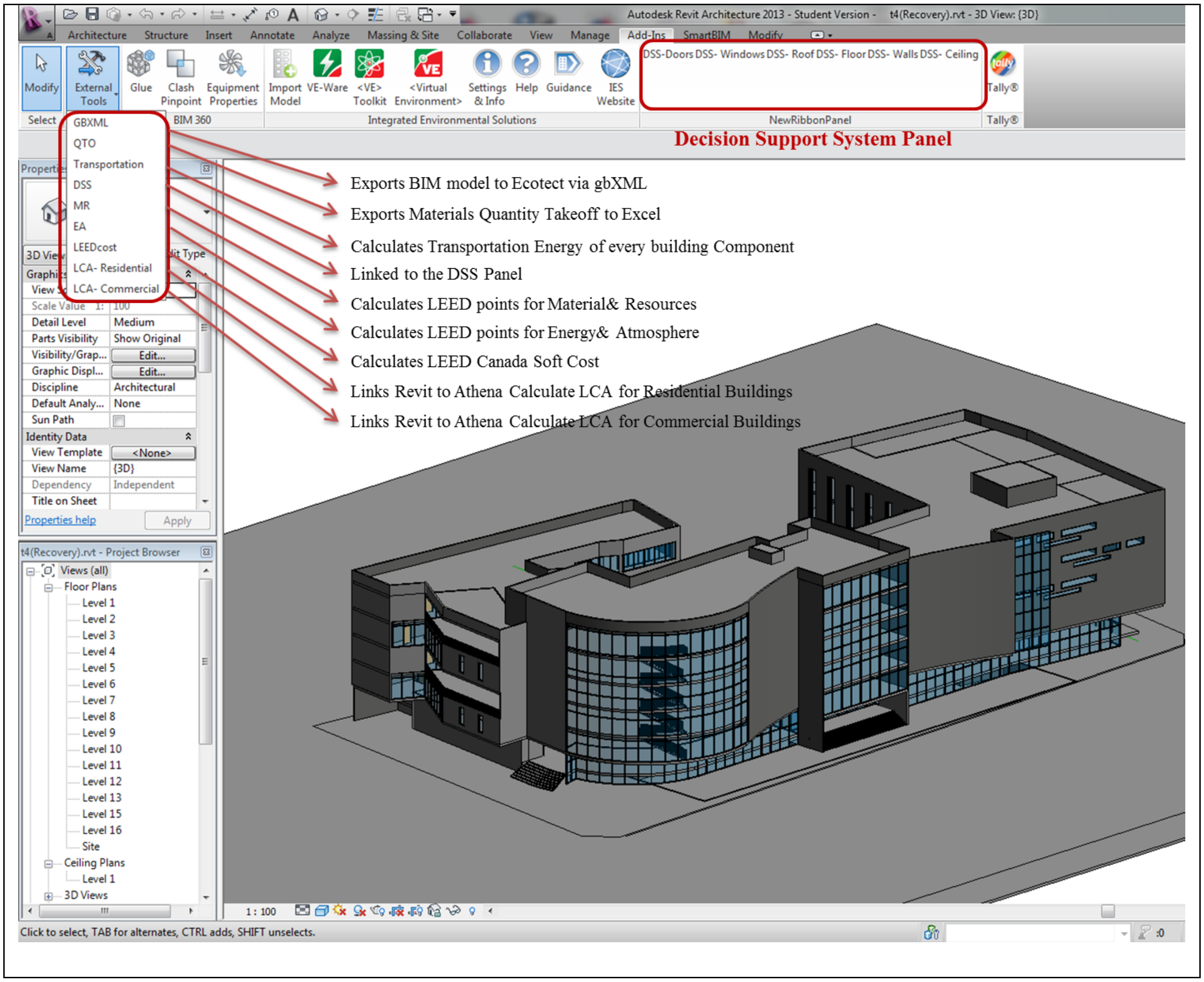
Appendixes

Appendix I

The Snapshot of the Developed Plug-ins



Appendix II

Decision Support System Survey Details

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid		3	10.7	10.7	10.7
	BACHELORS	1	3.6	3.6	14.3
	MASTERS	20	71.4	71.4	85.7
	PHD	4	14.3	14.3	100.0
	Total	28	100.0	100.0	

Education information of the experts to prepare criteria weight matrix

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1.00	1	3.6	4.0	4.0
	2.00	3	10.7	12.0	16.0
	3.00	1	3.6	4.0	20.0
	4.00	2	7.1	8.0	28.0
	5.00	5	17.9	20.0	48.0
	6.00	2	7.1	8.0	56.0
	7.00	1	3.6	4.0	60.0
	8.00	4	14.3	16.0	76.0
	9.00	2	7.1	8.0	84.0
	10.00	1	3.6	4.0	88.0
	13.00	1	3.6	4.0	92.0
	14.00	1	3.6	4.0	96.0
	97.00	1	3.6	4.0	100.0
	Total	25	89.3	100.0	

Project experience in Sustainability of the experts for the criteria weight matrix preparation

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	32.00	1	3.6	4.0	4.0
	35.00	4	14.3	16.0	20.0
	37.00	1	3.6	4.0	24.0
	38.00	1	3.6	4.0	28.0
	39.00	1	3.6	4.0	32.0
	45.00	3	10.7	12.0	44.0
	48.00	1	3.6	4.0	48.0
	49.00	2	7.1	8.0	56.0
	50.00	3	10.7	12.0	68.0
	51.00	2	7.1	8.0	76.0
	52.00	2	7.1	8.0	84.0
	54.00	2	7.1	8.0	92.0
	60.00	1	3.6	4.0	96.0
	65.00	1	3.6	4.0	100.0
	Total	25	89.3	100.0	
Missing	System	3	10.7		

Age distribution information of the experts for the criteria weight matrix preparation

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1.00	1	3.6	4.0	4.0
	2.00	1	3.6	4.0	8.0
	3.00	1	3.6	4.0	12.0
	5.00	4	14.3	16.0	28.0
	8.00	1	3.6	4.0	32.0
	9.00	3	10.7	12.0	44.0
	10.00	3	10.7	12.0	56.0
	12.00	2	7.1	8.0	64.0
	15.00	4	14.3	16.0	80.0
	17.00	1	3.6	4.0	84.0
	18.00	1	3.6	4.0	88.0
	20.00	1	3.6	4.0	92.0
	21.00	1	3.6	4.0	96.0
	35.00	1	3.6	4.0	100.0
	Total	25	89.3	100.0	

Decision making experience of the experts for the criteria weight matrix preparation

Dear Responder,

Thank you for accepting to participate in our survey " Building Projects Sustainable Criteria Evaluation Test".
This questionnaire is assessed to evaluate the inter-relationship between sustainability factors in building projects by expert point of views. In this questionnaire, you will asked to give values to the criteria relationship according to Saaty's 9 point scale.
This questionnaire has been made available as part of research by Farzad Jalaei and Dr. Ahmad Jrade from Department of Civil Engineering, University of Ottawa.
At the end of the questionnaire, background information will be asked. The questions are optional, but those will help our research.

Help	Inter-relationship Matrix	Environmental Impacts	Energy and Atmosphere	Material and Resources	Cost	Investment Criteria	Time	Construction Issues	Indoor Environmental Quality	Design & Architecture
Saaty's 9 point Scale	Environmental Impacts	1.00								
Scale1= Equally Important	Energy And Atmosphere		1.00							
Scale3= Weakly Important	Material And Resources			1.00						
Scale5= Strongly Important	Cost				1.00					
Scale7= Very Strongly Important	Investment Criteria					1.00				
Scale9= Extremely Important	Time						1.00			
	Construction Issues							1.00		
	Indoor Environmental Quality								1.00	
	Design & Architecture									1.00

Background Information:
1) Age:
2) Educational Degree: Graduate Diploma__ Bachelors__ Msters__ PhD
3) How many projects have you had with sustainability analysis requirement?
4) Have you had experience in Decision Making approaches? Yes__ No__

Study Criteria Weight Matrix Schema

Un-weighted Criteria matrix assembled by experts' opinions

	Environmental Impacts	Energy And Atmosphere	Material And Resources	Cost	Investment Criteria	Time	Construction Issues	Indoor Environmental Quality	Design & Architecture
Environmental Impacts	1.00	0.14	0.11	5.00	3.00	3.00	3.00	5.00	1.00
Energy And Atmosphere	7.00	1.00	0.17	6.00	5.00	1.00	1.00	7.00	1.00
Material And Resources	9.00	6.00	1.00	9.00	9.00	9.00	9.00	5.00	7.00
Cost	0.20	0.17	0.11	1.00	7.00	1.00	0.17	0.17	0.14
Investment Criteria	0.33	0.20	0.11	0.14	1.00	0.17	0.17	0.20	0.14
Time	0.33	1.00	0.11	1.00	6.00	1.00	7.00	1.00	1.00
Construction Issues	0.33	1.00	0.11	6.00	6.00	0.14	1.00	1.00	3.00
Indoor Environmental Quality	0.20	0.14	0.20	6.00	5.00	1.00	1.00	1.00	0.20
Design & Architecture	1.00	1.00	0.14	7.00	7.00	1.00	0.33	5.00	1.00

Normalized matrix By Entropy Method

Normalised Table	Environmental Impacts	Energy And Atmosphere	Material And Resources	Cost	Investment Criteria	Time	Construction Issues	Indoor Environmental Quality	Design & Architecture
Environmental Impacts	0.05	0.01	0.05	0.12	0.06	0.17	0.13	0.20	0.07
Energy And Atmosphere	0.36	0.09	0.08	0.15	0.10	0.06	0.04	0.28	0.07
Material And Resources	0.46	0.56	0.48	0.22	0.18	0.52	0.40	0.20	0.48
Cost	0.01	0.02	0.05	0.02	0.14	0.06	0.01	0.01	0.01
Investment Criteria	0.02	0.02	0.05	0.00	0.02	0.01	0.01	0.01	0.01
Time	0.02	0.09	0.05	0.02	0.12	0.06	0.31	0.04	0.07
Construction Issues	0.02	0.09	0.05	0.15	0.12	0.01	0.04	0.04	0.21
Indoor Environmental Quality	0.01	0.01	0.10	0.15	0.10	0.06	0.04	0.04	0.01
Design & Architecture	0.05	0.09	0.07	0.17	0.14	0.06	0.01	0.20	0.07

Calculated Entropy of the values by Entropy method

E_j	Environmental Impacts	Energy And Atmosphere	Material And Resources	Cost	Investment Criteria	Time	Construction Issues	Indoor Environmental Quality	Design & Architecture
Environmental Impacts	0.07	0.03	0.07	0.12	0.08	0.14	0.12	0.15	0.08
Energy And Atmosphere	0.17	0.10	0.09	0.13	0.11	0.07	0.06	0.16	0.08
Material And Resources	0.16	0.15	0.16	0.15	0.14	0.15	0.17	0.15	0.16
Cost	0.02	0.03	0.07	0.04	0.13	0.07	0.02	0.02	0.02
Investment Criteria	0.03	0.03	0.07	0.01	0.04	0.02	0.02	0.02	0.02
Time	0.03	0.10	0.07	0.04	0.12	0.07	0.17	0.06	0.08
Construction Issues	0.03	0.10	0.07	0.13	0.12	0.02	0.06	0.06	0.15
Indoor Environmental Quality	0.02	0.03	0.10	0.13	0.11	0.07	0.06	0.06	0.03
Design & Architecture	0.07	0.10	0.08	0.14	0.13	0.07	0.03	0.15	0.08
Total	0.61	0.67	0.80	0.88	0.95	0.71	0.70	0.81	0.71

Calculation of dj for Entropy method

$d_j = 1-E_j$	Environmental Impacts	Energy And Atmosphere	Material And Resources	Cost	Investment Criteria	Time	Construction Issues	Indoor Environmental Quality	Design & Architecture
	0.39	0.33	0.20	0.12	0.05	0.29	0.30	0.19	0.29

Weighted Entropy matrix

	Environmental Impacts	Energy And Atmosphere	Material And Resources	Cost	Investment Criteria	Time	Construction Issues	Indoor Environmental Quality	Design & Architecture
Environmental Impacts	0.18								
Energy And Atmosphere		0.15							
Material And Resources			0.09						
Cost				0.06					
Investment Criteria					0.02				
Time						0.14			
Construction Issues							0.14		
Indoor Environmental Quality								0.09	
Design & Architecture									0.13

Assembly Group	Company Name	Make/ Model
Doors	Karona	Door K-Square Karona
Doors	Karona	Door K-Ovolo Karona
Doors	Karona	Door K-Mission Karona
Doors	Karona	Door K-Ogee Karona
Doors	Kolbe & Kolbe Millwork Co	Sliding Patio Doors
Doors	Kolbe & Kolbe Millwork Co	Swinging Patio Doors
Doors	Kolbe & Kolbe Millwork Co	Folding Doors
Doors	Kolbe & Kolbe Millwork Co	Multi-Slide Doors
Doors	Kolbe & Kolbe Millwork Co	Ultra Series TerraSpan® Lift & Slide Doors
Doors	Kolbe & Kolbe Millwork Co	Entrance Doors
Doors	Kolbe & Kolbe Millwork Co	VistaLuxe Entrance Doors
Doors	Kolbe & Kolbe Millwork Co	Commercial Doors
Doors	Oldcastle BuildingEnvelope	Double Doors
Doors	Oldcastle BuildingEnvelope	Sidelite
Doors	Oldcastle BuildingEnvelope	Single Doors
Doors	Oldcastle BuildingEnvelope	Transom
Doors	Kawneer Co., Inc.	Double Doors
Doors	Kawneer Co., Inc.	Single Doors

Door assembly groups and their related information used in the database of DSS

Assembly Group	Company Name	Make/ Model
Roof	GAF (Conc, Mtl, Comp, Wood)	EnergyGuard™ PolyIso
Roof	GAF (Conc, Mtl, Comp, Wood)	EverGuard® Freedom™ TPO
Roof	GAF (Conc, Mtl, Comp, Wood)	Grand Canyon
Roof	GAF (Conc, Mtl, Comp, Wood)	Grand Sequoia® IR Shingles
Roof	GAF (Conc, Mtl, Comp, Wood)	RidGlass® (Antique Slate)
Roof	GAF (Conc, Mtl, Comp, Wood)	Royal Sovereign® Shingles (white)
Roof	GAF (Conc, Mtl, Comp, Wood)	Seal-A-Ridge®
Roof	GAF (Conc, Mtl, Comp, Wood)	Sentinel® Shingles (white)
Roof	GAF (Conc, Mtl, Comp, Wood)	Timberline® Cool Series

Roof assembly groups and their related information used in the database of DSS

Assembly Group	Company Name	Make/ Model
Floor	LATICRETE International, Inc. (Concrete)	Shower Floor
Floor	LATICRETE International, Inc. (Concrete)	Concrete - Thk and Thin Bed with PERMACOLOR Grout (Ext)
Floor	LATICRETE International, Inc. (Concrete)	Moisture Sensitive Tile or Stone - Epoxy Thin Bed with PERMACOLOR Grout
Floor	LATICRETE International, Inc. (Concrete)	Fiber Reinforced Gypsum Board with SPECTRALOCK PRO Premium Grout
Floor	Expanco (Vinyl)	Heirloom Cork Flooring
Floor	Expanco (Vinyl)	Reztec Recycled Rubber Flooring
Floor	Expanco (Vinyl)	XCR4 Cork/Rubber Flooring
Floor	Tandus Flooring, Inc. (Wood)	Abrasive Action II
Floor	Tandus Flooring, Inc. (Wood)	Accentuate
Floor	Tandus Flooring, Inc. (Wood)	Aftermath II
Floor	Tandus Flooring, Inc. (Wood)	All Star
Floor	Interstate Brick (Brick)	Almond
Floor	Interstate Brick (Brick)	Arctic White
Floor	Interstate Brick (Brick)	Ash
Floor	Interstate Brick (Brick)	Autumn Red
Floor	Interstate Brick (Brick)	Baja Brown
Floor	Interstate Brick (Brick)	Bronzestone
Floor	Interstate Brick (Brick)	Ochre Buff
Floor	Interstate Brick (Brick)	Sunset
Floor	Interstate Brick (Brick)	Walnut

Floor assembly groups and their related information used in the database of DSS

Assembly Group	Company Name	Make/ Model
Windows	Kolbe & Kolbe Millwork Co., Inc.	VistaLuxe™ Collection
Windows	Kolbe & Kolbe Millwork Co., Inc.	Ultra Series
Windows	Kolbe & Kolbe Millwork Co., Inc.	Heritage Series
Windows	Kolbe & Kolbe Millwork Co., Inc.	Windquest® Series
Windows	Milgard Manufacturing, Inc.	Style Line™ Series Windows
Windows	Milgard Manufacturing, Inc.	Tuscany Series Windows
Windows	Technical Glass Products	FireLite Plus®
Windows	Technical Glass Products	FireLite®
Windows	Technical Glass Products	FireLite® IGU
Windows	Technical Glass Products	FireLite® NT
Windows	Technical Glass Products	Fireframes SG Curtainwall™ Series
Windows	Technical Glass Products	Fireframes® Curtainwall Series
Windows	Technical Glass Products	Fireframes® Designer Series
Windows	Technical Glass Products	Fireframes® Heat Barrier Series
Windows	Technical Glass Products	LX X-Ray Shielding Glass
Windows	Technical Glass Products	Pilkington Profilit™
Windows	Technical Glass Products	Pilkington Profilit™ Hurricane LT
Windows	Technical Glass Products	Pilkington Profilit™ OW (Low-Iron)
Windows	Technical Glass Products	Pilkington Pyrostop® IGU
Windows	Technical Glass Products	SteelBuilt Curtainwall® Systems

Windows assembly groups and their related information used in the database of DSS

Assembly Group	Company Name	Make/ Model
Walls	CertainTeed (wood, gypsm)	1" GlasRoc Shaftliner 2x10 - Nashville, AR
Walls	CertainTeed (wood, gypsm)	1/2" AirRenew Essential Gypsum Board 54 inchx12
Walls	CertainTeed (wood, gypsm)	1/2" CertainTeed Type C 4x8 - Montreal, QC
Walls	CertainTeed (wood, gypsm)	1/2" CertainTeed Type C 4x10 - Toronto, ON
Walls	CertainTeed (wood, gypsm)	1/2" Easi-Lite Gypsum Board 4x8 - Toronto, ON
Walls	CertainTeed (wood, gypsm)	1/2" M2Tech 4x12 - Montreal, QC
Walls	CertainTeed (wood, gypsm)	5/8" CertainTeed Exterior Soffit Board Type C 4x8
Walls	CertainTeed (wood, gypsm)	5/8" CertainTeed Type X 4x14
Walls	Interstate brick (masonary, mtl)	Almond
Walls	Interstate brick (masonary, mtl)	Arctic White
Walls	Interstate brick (masonary, mtl)	Ash
Walls	Interstate brick (masonary, mtl)	Autumn Red
Walls	Interstate brick (masonary, mtl)	Baja Brown
Walls	Interstate brick (masonary, mtl)	Bronzestone
Walls	Interstate brick (masonary, mtl)	Ochre Buff
Walls	Interstate brick (masonary, mtl)	Sunset
Walls	Interstate brick (masonary, mtl)	Walnut
Walls	georgia pacific (Gypsm, glass)	Dens® Fiberglass Mat Gypsum Panels
Walls	georgia pacific (Gypsm, glass)	DensArmor Plus® Interior Panels
Walls	georgia pacific (Gypsm, glass)	ToughRock® Gypsum Boards and Drywall
Walls	georgia pacific (Gypsm, glass)	Gypsum Boards and Drywall (Canada)
Walls	LATICRETE International, Inc. (Concrete)	Cement Board Wall - Bed with SPECTRALOCK PRO Premium Grout
Walls	LATICRETE International, Inc. (Concrete)	Concrete Tub-Vert. - Thk and Thin Bed Over Lath with PERMACOLOR Grout
Walls	LATICRETE International, Inc. (Concrete)	Glass Mat WR Gypsum Board Tub Wall - Thk and Thin Bed with PERMACOLOR Grout
Walls	LATICRETE International, Inc. (Concrete)	Cement Coated Foam Board with PERMACOLOR Grout
Walls	LATICRETE International, Inc. (Concrete)	Fiber Reinforced WR Gypsum Board - Thin Bed with PERMACOLOR Grout
Walls	LATICRETE International, Inc. (Concrete)	Steel (Ext) - Thk Bed Over Lath with PERMACOLOR Grout
Walls	LATICRETE International, Inc. (Concrete)	Gypsum Board- Thk and Thin Bed with PERMACOLOR Grout
Walls	LATICRETE International, Inc. (Concrete)	Fiber-Reinforced WR Gypsum Board -Thk and Thin Bed with PERMACOLOR Grout

Walls assembly groups and their related information used in the database of DSS

Assembly Group	Company Name	Make/ Model
Ceiling	CertainTEED	15/16" Classic Aluminum Capped Hook Main Runn
Ceiling	CertainTEED	9/16" Smoothline Bolt Slot Cross Tee
Ceiling	CertainTEED	Cloud Perimeter Trim Curved
Ceiling	CertainTEED	Ecophon Focus Dg
Ceiling	CertainTEED	Ecophon VOC Compliant Focus E XL
Ceiling	CertainTEED	Gyptone BIG®
Ceiling	CertainTEED	Performa® Adagio
Ceiling	CertainTEED	Performa® Baroque® Customline
Ceiling	CertainTEED	Performa® Fine
Ceiling	CertainTEED	Performa® Open
Ceiling	CertainTEED	Performa® VOC
Ceiling	LATICRETE International, Inc. (Concrete)	C311 Ceilings (Concrete) - Bed with PERMACOLOR Grout
Ceiling	LATICRETE International, Inc. (Concrete)	C312 Ceilings (Gypsum Board) - Bed with PERMACOLOR Grout
Ceiling	LATICRETE International, Inc. (Concrete)	C315 Ceilings (Cement Board) - Bed with SPECTRALOCK PRO Premium Grout
Ceiling	LATICRETE International, Inc. (Concrete)	C512 Countertops - EGP with SPECTRALOCK PRO Premium Grout

Ceiling assembly groups and their related information used in the database of DSS

Appendix III

Codes of developed plug-ins using Microsoft Visual Studio

The plug-in which automatically exports BIM model into Ecotect via GBXML and IFC

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.Diagnostics;
using Autodesk.Revit.DB;
using Autodesk.Revit.DB.Architecture;
using Autodesk.Revit.UI;
using Autodesk.Revit.UI.Selection;
using Autodesk.Revit.ApplicationServices;
using Autodesk.Revit.Attributes;
using Autodesk.Revit.DB.Events;
using Autodesk.Revit;
using Autodesk.Revit.UI.Events;
[TransactionAttribute(TransactionMode.Manual)]
[RegenerationAttribute(RegenerationOption.Manual)]
public class GBXML : IExternalCommand
    {
        public Result Execute(
          ExternalCommandData commandData,
          ref string message,
          ElementSet elements)
        {
            SaveAsOptions sao = new SaveAsOptions();
            UIApplication uiApp = commandData.Application;
            Document doc = uiApp.ActiveUIDocument.Document;
            Transaction t = new Transaction(doc);
            t.Start("farzad");
            doc.Export("c:\\1\\", "gbxml",new GBXMLExportOptions());
            t.Commit();
            t.Start("farzad");
            doc.Export("c:\\1\\", "IFC", new IFCExportOptions());
            t.Commit();
            Process notePad = new Process();
            notePad.StartInfo.FileName = "Ecotect.exe";
            notePad.StartInfo.Arguments = "C:\\1\\gbxml.xml";
            notePad.Start();
            Reference pickedRef = null;
            Selection sel = uiApp.ActiveUIDocument.Selection;
            pickedRef = sel.PickObject(ObjectType.Element, "Please select a
group");
            Element elem = pickedRef.Element;
            Group group = elem as Group;
            XYZ point = sel.PickPoint("Please pick a point to place group");
            Transaction trans = new Transaction(doc);
            trans.Start("Lab");
```

```
            doc.Create.PlaceGroup(point, group.GroupType);
            trans.Commit();
            return Result.Succeeded;
        }
    }
```

The plug-in which connects BIM tool to LCA tool

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.Diagnostics;
using Autodesk.Revit.UI;
using Autodesk.Revit.Attributes;
using Autodesk.Revit.UI;
using Autodesk.Revit.DB;
using System;
    [TransactionAttribute(TransactionMode.Manual)]
    [RegenerationAttribute(RegenerationOption.Manual)]
    public class Class1: IExternalCommand
    {
        #region IExternalCommand Members
        public Result Execute(ExternalCommandData commandData, ref string
message, Autodesk.Revit.DB.ElementSet elements)
        {
            //Console.ReadLine();
            ProcessStartInfo startInfo = new ProcessStartInfo();
            startInfo.FileName = "excel.EXE";
            startInfo.Arguments = @"C:\Users\Jrade-
Grad1\Desktop\LCA\Athena.xlsm";
            Process.Start(startInfo);
            return Result.Succeeded;
        }
        #endregion
    }
```

The plug-in code developed to calculate LEED accrediting points for MR and EA credits

```
sing System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Windows.Forms;
using Microsoft.Office.Interop.Excel;
namespace FUMaterialResources
{
    public partial class Form1 : Form
    {
        Microsoft.Office.Interop.Excel.Range xlRange;
        int rowCount;
        int colCount;
        public Form1()
        {
            InitializeComponent();
        }
        private void Form1_Load(object sender, EventArgs e)
        {
            string file = @"C:\Users\Jrade-Grad1\Desktop\Book1.xlsx";
            Microsoft.Office.Interop.Excel.Application oexcel = new
Microsoft.Office.Interop.Excel.Application();
Microsoft.Office.Interop.Excel.Workbook wb = oexcel.Workbooks.Open(file, 0,
true, 5, "", "", true, Microsoft.Office.Interop.Excel.XlPlatform.xlWindows,
"\t", false, false, 0, true, 1, 0);
 Microsoft.Office.Interop.Excel._Worksheet xlWorksheet =
(Microsoft.Office.Interop.Excel._Worksheet)wb.Sheets[1];

            xlRange = xlWorksheet.UsedRange;
            rowCount = xlRange.Rows.Count;
            colCount = xlRange.Columns.Count;
            for (int i = 2; i <= rowCount; i++)
            {
                if
(!cmbBxAssemblyGroup.Items.Contains((string)(xlRange.Cells[i, 1] as
Microsoft.Office.Interop.Excel.Range).Value2.ToString()))
                {
cmbBxAssemblyGroup.Items.Add((string)(xlRange.Cells[i, 1] as
Microsoft.Office.Interop.Excel.Range).Value2);
                }
            }
        }
        private void btnLeedResult_Click(object sender, EventArgs e)
        {
            gvLeedResult.Visible = true;
            if (gvLeedResult.Columns.Count == 0)
            {
                for (int i = 1; i <= colCount; i++)
                {
gvLeedResult.Columns.Add("i", (string)(xlRange.Cells[1, i] as
Microsoft.Office.Interop.Excel.Range).Value2.ToString());
```

```
                }
            }
            List<String> dr = new List<String>();
            for (int i = 2; i <= rowCount; i++)
            {
                for (int j = 1; j <= colCount; j++)
                {
                if (cmbManufacturer.SelectedItem.ToString() ==
(string)(xlRange.Cells[i, 2] as
Microsoft.Office.Interop.Excel.Range).Value2.ToString() &&
cmbBxAssemblyGroup.SelectedItem.ToString() == (string)(xlRange.Cells[i, 1] as
Microsoft.Office.Interop.Excel.Range).Value2.ToString() &&
cmbProductLines.SelectedItem.ToString() == (string)(xlRange.Cells[i, 3] as
Microsoft.Office.Interop.Excel.Range).Value2.ToString())
                    {
                        if ((xlRange.Cells[i, j] as
Microsoft.Office.Interop.Excel.Range).Value2 != null)
                        {
                            dr.Add((string)(xlRange.Cells[i, j] as
Microsoft.Office.Interop.Excel.Range).Value2.ToString());
                        }
                        else
                        {
                            dr.Add(" ");
                        }
                    }
                }
            }
            gvLeedResult.Rows.Add(dr.ToArray());
        }
        private void cmbBxAssemblyGroup_SelectedIndexChanged(object sender,
EventArgs e)
        {
            cmbManufacturer.Enabled = true;
            cmbManufacturer.Items.Clear();
            cmbManufacturer.Items.Add("Select...");
            cmbManufacturer.SelectedIndex = 0;
            cmbManufacturer.Update();
            for (int i = 2; i <= rowCount; i++)
            {
                if (cmbBxAssemblyGroup.SelectedItem.ToString() ==
(string)(xlRange.Cells[i, 1] as
Microsoft.Office.Interop.Excel.Range).Value2.ToString())
                {
                    if
(!cmbManufacturer.Items.Contains((string)(xlRange.Cells[i, 2] as
Microsoft.Office.Interop.Excel.Range).Value2.ToString()))
                    {
            cmbManufacturer.Items.Add((string)(xlRange.Cells[i, 2] as
Microsoft.Office.Interop.Excel.Range).Value2);
                    }
                }
            }
        }
private void cmbManufacturer_SelectedIndexChanged(object sender, EventArgs e)
        {
            cmbProductLines.Enabled = true;
```

```
            cmbProductLines.Items.Clear();
            cmbProductLines.Items.Add("Select...");
            cmbProductLines.SelectedIndex = 0;
            cmbProductLines.Update();

            for (int i = 2; i <= rowCount; i++)
            {
  if (cmbBxAssemblyGroup.SelectedItem.ToString() == (string)(xlRange.Cells[i,
1] as Microsoft.Office.Interop.Excel.Range).Value2.ToString() &&
cmbManufacturer.SelectedItem.ToString() == (string)(xlRange.Cells[i, 2] as
Microsoft.Office.Interop.Excel.Range).Value2.ToString())
                {
  if (!cmbProductLines.Items.Contains((string)(xlRange.Cells[i, 3] as
Microsoft.Office.Interop.Excel.Range).Value2.ToString()))
                    {
 cmbProductLines.Items.Add((string)(xlRange.Cells[i, 3] as
Microsoft.Office.Interop.Excel.Range).Value2);
                    }
                }
            }
cmbProductLines.Enabled = true;
        }
        private void btnClrRes_Click(object sender, EventArgs e)
        {
            gvLeedResult.Rows.Clear();
            gvLeedResult.Columns.Clear();
        }
    }
}
```

The plug-in which connects BIM tool to LEED Canada Certification Calculator

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.Diagnostics;
using Autodesk.Revit.UI;
using Autodesk.Revit.Attributes;
using Autodesk.Revit.UI;
using Autodesk.Revit.DB;
using System;
    [TransactionAttribute(TransactionMode.Manual)]
    [RegenerationAttribute(RegenerationOption.Manual)]
    public class Class1: IExternalCommand
    {
        #region IExternalCommand Members
        public Result Execute(ExternalCommandData commandData, ref string
message, Autodesk.Revit.DB.ElementSet elements)
        {
            //Console.ReadLine();
            ProcessStartInfo startInfo = new ProcessStartInfo();
            startInfo.FileName = "excel.EXE";
```

```
            startInfo.Arguments = @"C:\Users\Jrade-
Grad1\Desktop\LEED\LEEDCan.xlsm";
            Process.Start(startInfo);

            return Result.Succeeded;
        }
        #endregion
    }
```

The plug-in code developed to calculate the transport Energy as a component of the embodied energy of building components

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Windows.Forms;
using System.Net;
using System.IO;
using System.Xml;
namespace FUTransportationEnergy
{
    public partial class Form1 : Form
    {
        public Form1()
        {
            InitializeComponent();
        }
        private void label2_Click(object sender, EventArgs e)
        {
        }
        private void textBox1_TextChanged(object sender, EventArgs e)
        {
        }
        private void btnCalculate_Click(object sender, EventArgs e)
        {
            door();


        }
        double doorMegaJ=0;
        private void door()
        {
            double[] doorT = { 0, 0, 0 };
            List<double> doorT4 = new List<double>();
            double doorWeight = Double.Parse(txtDoorWeight.Text); //
            txtDoorRes.Text += "Door:" + Environment.NewLine; //
            while (doorWeight >= 66200)
            {
              doorT4.Add(66200);
```

```
                doorWeight = doorWeight - 66200d;
            }
            if (55750 < doorWeight && doorWeight < 66200)
            {
                doorT4.Add(doorWeight);
            }
            else if (40800 < doorWeight && doorWeight <= 55750)
            {
                doorT[2] = doorWeight;
                txtDoorRes.Text += "Truck 3: " + doorWeight +
Environment.NewLine;
            }
            else if (25300 < doorWeight && doorWeight <= 40800)
            {
                doorT[1] = doorWeight;
                txtDoorRes.Text += "Truck 2: " + doorWeight +
Environment.NewLine;
            }
            else
            {
                doorT[0] = doorWeight;
                txtDoorRes.Text += "Truck 1: " + doorWeight +
Environment.NewLine;
            }
            foreach (double item in doorT4)
            {
                txtDoorRes.Text += "Truck 4: " + item + Environment.NewLine;
            }
            string url =
"http://maps.googleapis.com/maps/api/distancematrix/xml?origins="+txtDoorOrig
in.Text+"&destinations="+txtDoorDest.Text+"&mode=driving&language=en-
US&sensor=false&units=imperial"; //
            WebRequest request = WebRequest.Create(url);
            WebResponse response = request.GetResponse();
            Stream dataStream = response.GetResponseStream();
            StreamReader reader = new StreamReader(dataStream);
            string responseFromServer = reader.ReadToEnd();
            XmlDocument doc = new XmlDocument();
            doc.LoadXml(responseFromServer);
            XmlNodeList element = doc.GetElementsByTagName("distance");
            double distance =
double.Parse(element[0].ChildNodes[1].InnerText.Substring(0,
element[0].ChildNodes[1].InnerText.IndexOf("m")));
            double fuel = (distance / (-0.0263 * 66.2 + 5.885)) *
doorT4.Count + (distance / (-0.0255 * (doorT[2] / 1000) + 6.205)) * (doorT[2]
== 0 ? 0 : 1) + (distance / (-0.0258 * (doorT[1] / 1000) + 6.285)) *
(doorT[1] == 0 ? 0 : 1) + (distance / (-0.0246 * (doorT[0] / 1000) + 6.63)) *
(doorT[0] == 0 ? 0 : 1);
            doorMegaJ=fuel *= 131.76;
            txtDoorRes.Text += "Distance: " + distance.ToString() +
Environment.NewLine;
            txtDoorRes.Text += "Mega J: " + fuel.ToString() +
Environment.NewLine;
        }
     private void btnRoofCalculate_Click(object sender, EventArgs e)
        {
            roof();
```

```
        }
        double roofMegaJ=0;
        private void roof()
        {
            double[] roofT = { 0, 0, 0 };
            List<double> roofT4 = new List<double>();
            double roofWeight = Double.Parse(txtRoofWeight.Text); //
            textRoofRes.Text += "Roof:" + Environment.NewLine; //
            while (roofWeight >= 66200)
            {
                roofT4.Add(66200);
                roofWeight = roofWeight - 66200d;
            }
            if (55750 < roofWeight && roofWeight < 66200)
            {
                roofT4.Add(roofWeight);
            }
            else if (40800 < roofWeight && roofWeight <= 55750)
            {
                roofT[2] = roofWeight;
                textRoofRes.Text += "Truck 3: " + roofWeight +
Environment.NewLine;
            }
            else if (25300 < roofWeight && roofWeight <= 40800)
            {
                roofT[1] = roofWeight;
                textRoofRes.Text += "Truck 2: " + roofWeight +
Environment.NewLine;
            }
            else
            {
                roofT[0] = roofWeight;
                textRoofRes.Text += "Truck 1: " + roofWeight +
Environment.NewLine;
            }
            foreach (double item in roofT4)
            {
             textRoofRes.Text += "Truck 4: " + item + Environment.NewLine;
            }
            string url =
"http://maps.googleapis.com/maps/api/distancematrix/xml?origins=" +
txtRoofOrigin.Text + "&destinations=" + txtRoofDest.Text +
"&mode=driving&language=en-US&sensor=false&units=imperial"; //
            WebRequest request = WebRequest.Create(url);
            WebResponse response = request.GetResponse();
            Stream dataStream = response.GetResponseStream();
            StreamReader reader = new StreamReader(dataStream);
            string responseFromServer = reader.ReadToEnd();
            XmlDocument doc = new XmlDocument();
            doc.LoadXml(responseFromServer);
            XmlNodeList element = doc.GetElementsByTagName("distance");
            double distance =
double.Parse(element[0].ChildNodes[1].InnerText.Substring(0,
element[0].ChildNodes[1].InnerText.IndexOf("m")));
            double fuel = (distance / (-0.0263 * 66.2 + 5.885)) *
roofT4.Count + (distance / (-0.0255 * (roofT[2] / 1000) + 6.205)) * (roofT[2]
== 0 ? 0 : 1) + (distance / (-0.0258 * (roofT[1] / 1000) + 6.285)) *
```

```
(roofT[1] == 0 ? 0 : 1) + (distance / (-0.0246 * (roofT[0] / 1000) + 6.63)) *
(roofT[0] == 0 ? 0 : 1);
            roofMegaJ=fuel *= 131.76;
            textRoofRes.Text += "Distance: " + distance.ToString() +
Environment.NewLine;
            textRoofRes.Text += "Mega J: " + fuel.ToString() +
Environment.NewLine;
        }
           private void btnFloorCalculate_Click(object sender, EventArgs e)
           {
               floor();
           }
           double floorMegaJ=0;
         private void floor()
        {
            double[] floorT = { 0, 0, 0 };
            List<double> floorT4 = new List<double>();
            double FloorWeight = Double.Parse(txtFloorWeight.Text); //
            textFloorRes.Text += "Floor:" + Environment.NewLine; //
            while (FloorWeight >= 66200)
            {
                floorT4.Add(66200);
                FloorWeight = FloorWeight - 66200d;
            }
            if (55750 < FloorWeight && FloorWeight < 66200)
            {
                floorT4.Add(FloorWeight);
            }
            else if (40800 < FloorWeight && FloorWeight <= 55750)
            {
                floorT[2] = FloorWeight;
                textFloorRes.Text += "Truck 3: " + FloorWeight +
Environment.NewLine;
            }
            else if (25300 < FloorWeight && FloorWeight <= 40800)
            {
                floorT[1] = FloorWeight;
                textFloorRes.Text += "Truck 2: " + FloorWeight +
Environment.NewLine;
            }
            else
            {
                floorT[0] = FloorWeight;
                textFloorRes.Text += "Truck 1: " + FloorWeight +
Environment.NewLine;
            }
            foreach (double item in floorT4)
            {
                textFloorRes.Text += "Truck 4: " + item +
Environment.NewLine;
            }
            string url =
"http://maps.googleapis.com/maps/api/distancematrix/xml?origins=" +
txtFloorOrigin.Text + "&destinations=" + txtFloorDest.Text +
"&mode=driving&language=en-US&sensor=false&units=imperial"; //
            WebRequest request = WebRequest.Create(url);
            WebResponse response = request.GetResponse();
```

```
            Stream dataStream = response.GetResponseStream();
            StreamReader reader = new StreamReader(dataStream);
            string responseFromServer = reader.ReadToEnd();
            XmlDocument doc = new XmlDocument();
            doc.LoadXml(responseFromServer);
            XmlNodeList element = doc.GetElementsByTagName("distance");
            double distance =
double.Parse(element[0].ChildNodes[1].InnerText.Substring(0,
element[0].ChildNodes[1].InnerText.IndexOf("m")));
            double fuel = (distance / (-0.0263 * 66.2 + 5.885)) *
floorT4.Count + (distance / (-0.0255 * (floorT[2] / 1000) + 6.205)) *
(floorT[2] == 0 ? 0 : 1) + (distance / (-0.0258 * (floorT[1] / 1000) +
6.285)) * (floorT[1] == 0 ? 0 : 1) + (distance / (-0.0246 * (floorT[0] /
1000) + 6.63)) * (floorT[0] == 0 ? 0 : 1);
            floorMegaJ = fuel *= 131.76;
            textFloorRes.Text += "Distance: " + distance.ToString() +
Environment.NewLine;
            textFloorRes.Text += "Mega J: " + fuel.ToString() +
Environment.NewLine;
        }
         private void btnWallCalculate_Click(object sender, EventArgs e)
         {
             Wall();
         }
         double wallMegaJ=0;
         private void Wall()
         {

             double[] wallT = { 0, 0, 0 };
             List<double> wallT4 = new List<double>();
             double WallWeight = Double.Parse(txtWallWeight.Text); //
             textWallRes.Text += "Wall:" + Environment.NewLine; //
             while (WallWeight >= 66200)
             {
                 wallT4.Add(66200);
                 WallWeight = WallWeight - 66200d;
             }
             if (55750 < WallWeight && WallWeight < 66200)
             {
                 wallT4.Add(WallWeight);
             }
             else if (40800 < WallWeight && WallWeight <= 55750)
             {
                 wallT[2] = WallWeight;
                 textWallRes.Text += "Truck 3: " + WallWeight +
Environment.NewLine;
             }
             else if (25300 < WallWeight && WallWeight <= 40800)
             {
                 wallT[1] = WallWeight;
                 textWallRes.Text += "Truck 2: " + WallWeight +
Environment.NewLine;
             }
             else
             {
                 wallT[0] = WallWeight;
                 textWallRes.Text += "Truck 1: " + WallWeight +
```

```
Environment.NewLine;
                }
                foreach (double item in wallT4)
                {
                textWallRes.Text += "Truck 4: " + item + Environment.NewLine;
                }
                string url =
"http://maps.googleapis.com/maps/api/distancematrix/xml?origins=" +
txtWallOrigin.Text + "&destinations=" + txtWallDest.Text +
"&mode=driving&language=en-US&sensor=false&units=imperial"; //
                WebRequest request = WebRequest.Create(url);
                WebResponse response = request.GetResponse();
                Stream dataStream = response.GetResponseStream();
                StreamReader reader = new StreamReader(dataStream);
                string responseFromServer = reader.ReadToEnd();
                XmlDocument doc = new XmlDocument();
                doc.LoadXml(responseFromServer);
                XmlNodeList element = doc.GetElementsByTagName("distance");
                double distance =
double.Parse(element[0].ChildNodes[1].InnerText.Substring(0,
element[0].ChildNodes[1].InnerText.IndexOf("m")));
                double fuel = (distance / (-0.0263 * 66.2 + 5.885)) *
wallT4.Count + (distance / (-0.0255 * (wallT[2] / 1000) + 6.205)) * (wallT[2]
== 0 ? 0 : 1) + (distance / (-0.0258 * (wallT[1] / 1000) + 6.285)) *
(wallT[1] == 0 ? 0 : 1) + (distance / (-0.0246 * (wallT[0] / 1000) + 6.63)) *
(wallT[0] == 0 ? 0 : 1);
                wallMegaJ = fuel *= 131.76;
                textWallRes.Text += "Distance: " + distance.ToString() +
Environment.NewLine;
                textWallRes.Text += "Mega J: " + fuel.ToString() +
Environment.NewLine;
            }
            private void btnWindowsCalculate_Click(object sender, EventArgs e)
            {
                Windows();
            }
            double windowsMegaJ=0;
            private void Windows()

            {
                double[] windowsT = { 0, 0, 0 };
                List<double> windowsT4 = new List<double>();
                double WindowsWeight = Double.Parse(txtWindowsWeight.Text);
textWindowsRes.Text += "Windows:" + Environment.NewLine;
                while (WindowsWeight >= 66200)
                {
                    windowsT4.Add(66200);
                    WindowsWeight = WindowsWeight - 66200d;
                }
                if (55750 < WindowsWeight && WindowsWeight < 66200)
                {
                    windowsT4.Add(WindowsWeight);
                }
                else if (40800 < WindowsWeight && WindowsWeight <= 55750)
                {
                    windowsT[2] = WindowsWeight;
                    textWindowsRes.Text += "Truck 3: " + WindowsWeight +
```

```
Environment.NewLine;
                }
                else if (25300 < WindowsWeight && WindowsWeight <= 40800)
                {
                    windowsT[1] = WindowsWeight;
                    textWindowsRes.Text += "Truck 2: " + WindowsWeight +
Environment.NewLine;
                }
                else
                {
                    windowsT[0] = WindowsWeight;
                    textWindowsRes.Text += "Truck 1: " + WindowsWeight +
Environment.NewLine;
                }
                foreach (double item in windowsT4)
                {
                    textWindowsRes.Text += "Truck 4: " + item +
Environment.NewLine;
                }
                string url =
"http://maps.googleapis.com/maps/api/distancematrix/xml?origins=" +
txtWindowsOrigin.Text + "&destinations=" + txtWindowsDest.Text +
"&mode=driving&language=en-US&sensor=false&units=imperial";
                WebRequest request = WebRequest.Create(url);
                WebResponse response = request.GetResponse();
                Stream dataStream = response.GetResponseStream();
                StreamReader reader = new StreamReader(dataStream);
                string responseFromServer = reader.ReadToEnd();
                XmlDocument doc = new XmlDocument();
                doc.LoadXml(responseFromServer);
                XmlNodeList element = doc.GetElementsByTagName("distance");
                double distance =
double.Parse(element[0].ChildNodes[1].InnerText.Substring(0,
element[0].ChildNodes[1].InnerText.IndexOf("m")));
                double fuel = (distance / (-0.0263 * 66.2 + 5.885)) *
windowsT4.Count + (distance / (-0.0255 * (windowsT[2] / 1000) + 6.205)) *
(windowsT[2] == 0 ? 0 : 1) + (distance / (-0.0258 * (windowsT[1] / 1000) +
6.285)) * (windowsT[1] == 0 ? 0 : 1) + (distance / (-0.0246 * (windowsT[0] /
1000) + 6.63)) * (windowsT[0] == 0 ? 0 : 1);
                windowsMegaJ = fuel *= 131.76;
                textWindowsRes.Text += "Distance: " + distance.ToString() +
Environment.NewLine;
                textWindowsRes.Text += "Mega J: " + fuel.ToString() +
Environment.NewLine;
            }
            private void btnTotal_Click(object sender, EventArgs e)
            {
                textTotalRes.Text += "Total Transportation Energy" +
(windowsMegaJ+ wallMegaJ +  floorMegaJ +  roofMegaJ +  doorMegaJ);
            }
            private void Result_Enter(object sender, EventArgs e)
            {
            }
            private void Form1_Load(object sender, EventArgs e)
            {
            }
```

The Decision Support System plug-in code for door components

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Windows.Forms;
using System.Collections;
    public struct StrDouble: IComparable
    {
        public StrDouble(double di,string si)
        {
            output = di;
            link = si;
        }
        public string link;
        public double output;
        #region IComparable Members
        public int CompareTo(object obj)
        {
            if (this.output>((StrDouble)obj).output)
            {
                return 1;
            }
            else if (this.output < ((StrDouble)obj).output)
            {
                return -1;
            }
            else
            {
                return 0;
            }
        }
        #endregion
    }
        public partial class Form1 : Form
    {
        public Form1()
        {
            InitializeComponent();
        }
        private void linkLabel1_LinkClicked(object sender,
LinkLabelLinkClickedEventArgs e)
        {
System.Diagnostics.Process.Start("http://library.smartbim.com/models/0/Door%2
0K6010-Square%20Karona");
        }
        private void linkLabel2_LinkClicked(object sender,
LinkLabelLinkClickedEventArgs e)
        {
System.Diagnostics.Process.Start("http://library.smartbim.com/models/0/Door%2
0K6020-Ovolo%20Karona");
        }
```

```
        private void linkLabel3_LinkClicked(object sender,
LinkLabelLinkClickedEventArgs e)
        {
System.Diagnostics.Process.Start("http://library.smartbim.com/models/0/Door%2
0K6010-Mission%20Karona");
        }
        private void linkLabel4_LinkClicked(object sender,
LinkLabelLinkClickedEventArgs e)
        {
System.Diagnostics.Process.Start("http://library.smartbim.com/models/0/Door%2
0K7300-Ogee%20Karona");
        }
        private void linkLabel8_LinkClicked(object sender,
LinkLabelLinkClickedEventArgs e)
        {
            System.Diagnostics.Process.Start("http://www.kolbe-
kolbe.com/products/index.cfm?pcID=4&pID=68&pCat=11");
        }
        private void linkLabel7_LinkClicked(object sender,
LinkLabelLinkClickedEventArgs e)
        {
            System.Diagnostics.Process.Start("http://www.kolbe-
kolbe.com/products/index.cfm?pcID=4&pID=68&pCat=12");
        }
        private void linkLabel6_LinkClicked(object sender,
LinkLabelLinkClickedEventArgs e)
        {
            System.Diagnostics.Process.Start("http://www.kolbe-
kolbe.com/products/index.cfm?pcID=4&pID=68&pCat=19");
        }
        private void linkLabel5_LinkClicked(object sender,
LinkLabelLinkClickedEventArgs e)
        {
            System.Diagnostics.Process.Start("http://www.kolbe-
kolbe.com/products/index.cfm?pcID=4&pID=68&pCat=23");
        }
        private void linkLabel9_LinkClicked(object sender,
LinkLabelLinkClickedEventArgs e)
        {
            System.Diagnostics.Process.Start("http://www.kolbe-
kolbe.com/products/index.cfm?pcID=4&pID=68&pCat=15");
        }
        private void linkLabel10_LinkClicked(object sender,
LinkLabelLinkClickedEventArgs e)
        {
            System.Diagnostics.Process.Start("http://www.kolbe-
kolbe.com/products/index.cfm?pcID=4&pID=70&pCat=24&pSubCat=0&pl=150");
        }
        private void linkLabel12_LinkClicked(object sender,
LinkLabelLinkClickedEventArgs e)
        {
            System.Diagnostics.Process.Start("http://www.kolbe-
kolbe.com/products/index.cfm?pcID=4&pID=68&pCat=16");
        }
        private void linkLabel16_LinkClicked(object sender,
LinkLabelLinkClickedEventArgs e)
        {
```

```
System.Diagnostics.Process.Start("http://www.kawneer.com/kawneer/north_americ
a/en/product_category.asp?cat_id=1340");
        }
        private void linkLabel11_LinkClicked(object sender,
LinkLabelLinkClickedEventArgs e)
        {
System.Diagnostics.Process.Start("http://www.kawneer.com/kawneer/north_americ
a/en/product_category.asp?cat_id=1912");
        }
        private void btnWallCalculate_Click(object sender, EventArgs e)
        {
            double[,] weightcriterion = new double[9, 9];
            for (int i = 0; i < 9; i++)
            {
                for (int j = 0; j < 9; j++)
                {
                weightcriterion[i, j] = 0;
                }
            }
            weightcriterion[0, 0] = 0.18;
            weightcriterion[1, 1] = 0.15;
            weightcriterion[7, 7] = weightcriterion[2, 2] = 0.09;
            weightcriterion[3, 3] = 0.06;
            weightcriterion[4, 4] = 0.02;
            weightcriterion[5, 5] = weightcriterion[6, 6] = 0.14;
            weightcriterion[8, 8] = 0.13;
            double[,] weight = new double[13, 9];
            weight[0, 0] = Double.Parse(textBox1.Text == "" ? "1" :
textBox1.Text);
            weight[0, 1] = Double.Parse(textBox2.Text);
            weight[0, 2] = Double.Parse(textBox3.Text);
            weight[0, 3] = Double.Parse(textBox23.Text);
            weight[0, 4] = Double.Parse(textBox24.Text);
            weight[0, 5] = Double.Parse(textBox22.Text);
            weight[0, 6] = Double.Parse(textBox25.Text);
            weight[0, 7] = Double.Parse(textBox44.Text);
            weight[0, 8] = Double.Parse(textBox41.Text);
            weight[1, 0] = Double.Parse(textBox4.Text);
            weight[1, 1] = Double.Parse(textBox5.Text);
            weight[1, 2] = Double.Parse(textBox6.Text);
            weight[1, 3] = Double.Parse(textBox16.Text);
            weight[1, 4] = Double.Parse(textBox15.Text);
            weight[1, 5] = Double.Parse(textBox14.Text);
            weight[1, 6] = Double.Parse(textBox13.Text);
            weight[1, 7] = Double.Parse(textBox30.Text);
            weight[1, 8] = Double.Parse(textBox29.Text);
            weight[2, 0] = Double.Parse(textBox7.Text);
            weight[2, 1] = Double.Parse(textBox8.Text);
            weight[2, 2] = Double.Parse(textBox9.Text);
            weight[2, 3] = Double.Parse(textBox20.Text);
            weight[2, 4] = Double.Parse(textBox19.Text);
            weight[2, 5] = Double.Parse(textBox18.Text);
            weight[2, 6] = Double.Parse(textBox17.Text);
            weight[2, 7] = Double.Parse(textBox32.Text);
            weight[2, 8] = Double.Parse(textBox31.Text);
            weight[3, 0] = Double.Parse(textBox10.Text);
            weight[3, 1] = Double.Parse(textBox11.Text);
```

```
            weight[3, 2] = Double.Parse(textBox12.Text);
            weight[3, 3] = Double.Parse(textBox28.Text);
            weight[3, 4] = Double.Parse(textBox27.Text);
            weight[3, 5] = Double.Parse(textBox26.Text);
            weight[3, 6] = Double.Parse(textBox21.Text);
            weight[3, 7] = Double.Parse(textBox34.Text);
            weight[3, 8] = Double.Parse(textBox33.Text);
            weight[4, 0] = Double.Parse(textBox48.Text);
            weight[4, 1] = Double.Parse(textBox47.Text);
            weight[4, 2] = Double.Parse(textBox46.Text);
            weight[4, 3] = Double.Parse(textBox70.Text);
            weight[4, 4] = Double.Parse(textBox69.Text);
            weight[4, 5] = Double.Parse(textBox68.Text);
            weight[4, 6] = Double.Parse(textBox67.Text);
            weight[4, 7] = Double.Parse(textBox86.Text);
            weight[4, 8] = Double.Parse(textBox85.Text);
            weight[5, 0] = Double.Parse(textBox37.Text);
            weight[5, 1] = Double.Parse(textBox36.Text);
            weight[5, 2] = Double.Parse(textBox35.Text);
            weight[5, 3] = Double.Parse(textBox66.Text);
            weight[5, 4] = Double.Parse(textBox65.Text);
            weight[5, 5] = Double.Parse(textBox64.Text);
            weight[5, 6] = Double.Parse(textBox63.Text);
            weight[5, 7] = Double.Parse(textBox84.Text);
            weight[5, 8] = Double.Parse(textBox83.Text);
            weight[6, 0] = Double.Parse(textBox40.Text);
            weight[6, 1] = Double.Parse(textBox39.Text);
            weight[6, 2] = Double.Parse(textBox38.Text);
            weight[6, 3] = Double.Parse(textBox62.Text);
            weight[6, 4] = Double.Parse(textBox61.Text);
            weight[6, 5] = Double.Parse(textBox60.Text);
            weight[6, 6] = Double.Parse(textBox59.Text);
            weight[6, 7] = Double.Parse(textBox82.Text);
            weight[6, 8] = Double.Parse(textBox81.Text);
            weight[7, 0] = Double.Parse(textBox45.Text);
            weight[7, 1] = Double.Parse(textBox43.Text);
            weight[7, 2] = Double.Parse(textBox42.Text);
            weight[7, 3] = Double.Parse(textBox58.Text);
            weight[7, 4] = Double.Parse(textBox57.Text);
            weight[7, 5] = Double.Parse(textBox56.Text);
            weight[7, 6] = Double.Parse(textBox55.Text);
            weight[7, 7] = Double.Parse(textBox80.Text);
            weight[7, 8] = Double.Parse(textBox79.Text);
            weight[8, 0] = Double.Parse(textBox51.Text);
            weight[8, 1] = Double.Parse(textBox50.Text);
            weight[8, 2] = Double.Parse(textBox49.Text);
            weight[8, 3] = Double.Parse(textBox74.Text);
            weight[8, 4] = Double.Parse(textBox73.Text);
            weight[8, 5] = Double.Parse(textBox72.Text);
            weight[8, 6] = Double.Parse(textBox71.Text);
            weight[8, 7] = Double.Parse(textBox88.Text);
            weight[8, 8] = Double.Parse(textBox87.Text);
            weight[9, 0] = Double.Parse(textBox54.Text);
            weight[9, 1] = Double.Parse(textBox53.Text);
            weight[9, 2] = Double.Parse(textBox52.Text);
            weight[9, 3] = Double.Parse(textBox78.Text);
            weight[9, 4] = Double.Parse(textBox77.Text);
```

```
weight[9, 5] = Double.Parse(textBox76.Text);
weight[9, 6] = Double.Parse(textBox75.Text);
weight[9, 7] = Double.Parse(textBox90.Text);
weight[9, 8] = Double.Parse(textBox89.Text);
weight[10, 0] = Double.Parse(textBox93.Text);
weight[10, 1] = Double.Parse(textBox92.Text);
weight[10, 2] = Double.Parse(textBox91.Text);
weight[10, 3] = Double.Parse(textBox99.Text);
weight[10, 4] = Double.Parse(textBox96.Text);
weight[10, 5] = Double.Parse(textBox95.Text);
weight[10, 6] = Double.Parse(textBox94.Text);
weight[10, 7] = Double.Parse(textBox101.Text);
weight[10, 8] = Double.Parse(textBox100.Text);
weight[11, 0] = Double.Parse(textBox126.Text);
weight[11, 1] = Double.Parse(textBox125.Text);
weight[11, 2] = Double.Parse(textBox124.Text);
weight[11, 3] = Double.Parse(textBox135.Text);
weight[11, 4] = Double.Parse(textBox134.Text);
weight[11, 5] = Double.Parse(textBox133.Text);
weight[11, 6] = Double.Parse(textBox132.Text);
weight[11, 7] = Double.Parse(textBox137.Text);
weight[11, 8] = Double.Parse(textBox136.Text);
weight[12, 0] = Double.Parse(textBox120.Text);
weight[12, 1] = Double.Parse(textBox98.Text);
weight[12, 2] = Double.Parse(textBox97.Text);
weight[12, 3] = Double.Parse(textBox131.Text);
weight[12, 4] = Double.Parse(textBox130.Text);
weight[12, 5] = Double.Parse(textBox129.Text);
weight[12, 6] = Double.Parse(textBox128.Text);
weight[12, 7] = Double.Parse(textBox127.Text);
weight[12, 8] = Double.Parse(textBox123.Text);
double sum_weight = 0;
for (int i = 0; i < weight.GetLength(0); i++)
{
    for (int j = 0; j < weight.GetLength(1); j++)
    {
        sum_weight += Math.Pow(weight[i, j], 2);
    }
}
sum_weight = Math.Sqrt(sum_weight);
for (int i = 0; i < weight.GetLength(0); i++)
{
    for (int j = 0; j < weight.GetLength(1); j++)
    {
        weight[i, j] = (Math.Pow(weight[i, j], 2) / sum_weight);
    }
}
double[] output = Topsis.TOPSIS(weightcriterion, weight);
List<StrDouble> sl = new List<StrDouble>();
int cnt = 0;
foreach (var gb in this.Controls)
{if (gb.GetType() == groupBox13.GetType())
    {foreach (var ll in ((GroupBox)gb).Controls)
        {
            if (ll.GetType() == linkLabel1.GetType())
            {
                sl.Add(new StrDouble(output[cnt],
```

```
((GroupBox)gb).Text + ((LinkLabel)ll).Text));
                            cnt++;
                        }
                    }
                }
            }
            sl.Sort();
            sl.Reverse();
            txtDoorRes.Text = "";
            foreach (var item in sl)
            {
                txtDoorRes.Text += item.link + " (" + item.output.ToString()
+ ")" + System.Environment.NewLine;
            }
            }
        private void button1_Click(object sender, EventArgs e)
        {
            PopupWindow popup = new PopupWindow();
            popup.ShowDialog();
        }
    }
    public class Topsis
    {
  public static double[] TOPSIS(double[,] weightcriterion, double[,] weight)
        {
            double[] sumsofwights = new double[weight.GetLength(1)];
            for (int j = 0; j < weight.GetLength(1); j++)
                for (int i = 0; i < weight.GetLength(0); i++)
                    sumsofwights[j] += weight[i, j];
            for (int j = 0; j < weight.GetLength(1); j++)
            for (int i = 0; i < weight.GetLength(0); i++)
                    weight[i, j] = Math.Round(weight[i, j] / sumsofwights[j],
4, MidpointRounding.AwayFromZero);
            sumsofwights = null;
            double[] avgofwights = new double[weight.GetLength(0)];
            for (int i = 0; i < weight.GetLength(0); i++)
                for (int j = 0; j < weight.GetLength(1); j++)
                    avgofwights[i] += weight[i, j];
                for (int i = 0; i < avgofwights.Length; i++)
                avgofwights[i] = Math.Round(avgofwights[i] /
weight.GetLength(1), 4, MidpointRounding.AwayFromZero);
               avgofwights = null;
             double[,] multiply = new double[weight.GetLength(0),
weight.GetLength(1)];
            for (int i = 0; i < weight.GetLength(0); i++)
                for (int j = 0; j < weight.GetLength(1); j++)
                    multiply[i, j] = Math.Round(weight[i, j] *
weightcriterion[j, j], 5, MidpointRounding.AwayFromZero);
            logMatrix(multiply);
            double[] mins = new double[multiply.GetLength(1)];
            for (int i = 0; i < mins.Length; i++)
                mins[i] = double.MaxValue;
            double[] maxs = new double[multiply.GetLength(1)];
            for (int i = 0; i < mins.Length; i++)
                maxs[i] = double.MinValue;
            for (int j = 0; j < multiply.GetLength(1); j++)
            for (int i = 0; i < multiply.GetLength(0); i++)
```

```
                {
                    mins[j] = Math.Min(mins[j], multiply[i, j]);
                    maxs[j] = Math.Max(maxs[j], multiply[i, j]);
                }
            double[,] DPlus = new double[multiply.GetLength(0),
multiply.GetLength(1) + 2];
            double[,] Dminus = new double[multiply.GetLength(0),
multiply.GetLength(1) + 2];
            for (int i = 0; i < multiply.GetLength(0); i++)
            for (int j = 0; j < multiply.GetLength(1); j++)
                {
                    DPlus[i, j] = Math.Round(Math.Pow(multiply[i, j] -
maxs[j], 2), 9, MidpointRounding.AwayFromZero);
                    Dminus[i, j] = Math.Round(Math.Pow(multiply[i, j] -
mins[j], 2), 9, MidpointRounding.AwayFromZero);
                }
            for (int i = 0; i < DPlus.GetLength(0); i++)
            for (int j = 0; j < DPlus.GetLength(1) - 2; j++)
                {
                    DPlus[i, DPlus.GetLength(1) - 2] += DPlus[i, j];
                    Dminus[i, Dminus.GetLength(1) - 2] += Dminus[i, j];
                }
           for (int i = 0; i < DPlus.GetLength(0); i++)
            {
                DPlus[i, DPlus.GetLength(1) - 1] =
Math.Round(Math.Sqrt(DPlus[i, DPlus.GetLength(1) - 2]), 9,
MidpointRounding.AwayFromZero);
                Dminus[i, Dminus.GetLength(1) - 1] =
Math.Round(Math.Sqrt(Dminus[i, Dminus.GetLength(1) - 2]), 9,
MidpointRounding.AwayFromZero);
            }
            double[] output = new double[DPlus.GetLength(0)];
            for (int i = 0; i < DPlus.GetLength(0); i++)
                output[i] = Math.Round(Dminus[i, Dminus.GetLength(1) - 1] /
(Dminus[i, Dminus.GetLength(1) - 1] + DPlus[i, DPlus.GetLength(1) - 1]), 4,
MidpointRounding.AwayFromZero);
            return output;
        }
        public static void logMatrix(double[,] array)
        {for (int i = 0; i < array.GetLength(0); i++)
            {
                for (int j = 0; j < array.GetLength(1); j++)
                {
                    System.Diagnostics.Debug.Write(array[i, j].ToString("n6")
+ "  ");        }
                System.Diagnostics.Debug.WriteLine("");
            }
            System.Diagnostics.Debug.WriteLine("");
        }
        public static void logMatrix(double[] array)
        {
            for (int i = 0; i < array.GetLength(0); i++)
            {System.Diagnostics.Debug.Write(array[i] + "  ");
            }
            System.Diagnostics.Debug.WriteLine("");    }
```