INTEGRATING BUILDING INFORMATION MODELING AND GREEN BUILDING CERTIFICATION: THE BIM – LEED APPLICATION MODEL DEVELOPMENT

By

WEI WU

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2010

To my family

ACKNOWLEDGMENTS

I would like to give my deepest gratitude to my chair Dr. Issa, a great mentor who leads me into the wonderland of building information modeling, and my co-chair Dr. Kibert who teaches me the world's most beautiful color is green. I thank my wonderful committee members, Dr. Ries, Dr. Olbina and Dr. Chow. Their profound knowledge and persistent encouragement navigate me through one of the most challenging stages in my life.

I would like to thank all BCN faculty, who I have been fortunately enough to learn from and work with for the last four years. I also want to thank the whole BCN staff team for their willingness to help out.

I am indebted to Autodesk for their generosity to authorize me access to the resources that have been invaluable to my research.

I want to tell my wife that she is the one and only angel in my life; I want to tell my family how much I love them. Without them being there for me, my life is meaningless.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AEC	Architecture, Engineering and Construction
ANSI	American National Standards Institute
API	Application Programming Interface
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIM	Building Information Modeling
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency
CFM	Cubic Feet per Minute
CIS/2	CIMSteel Integration Standards
CLI	Common Language Infrastructure
DLL	Dynamic-link Library
DOM	Domain Object Model
FTE	Full-time Equivalent
FSC	Forest Stewardship Council
GBCI	Green Building Certification Institute
GBI	Green Building Initiative
GBS	Green Building Studio
gbXML	Green Building eXtensible Markup Language
GSA	General Service Administration
GUI	Graphical User Interface
GUID	Global Unique Identifier
I/O	Input/output

IAI	International Alliance for Interoperability
ICC	International Code Council
IDM	Information Delivery Manual
IES	Illuminating Engineering Society
IES<VE>	Integrated Environmental Solutions <Virtual Environment>
IFC	Industry Foundation Class
IFD	International Framework for Dictionaries
IGCC	International Green Construction Code
ISO	International Organization for Standardization
LEED	Leadership in Energy and Environmental Design
LEED AP	LEED Accredited Professional
LEED-NC	LEED for New Construction
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LCGWP	Life Cycle Global Warming Potential
LCODP	Life Cycle Ozone Depletion Potential
MEP	Mechanical, Electrical and Plumbing
MPR	Minimum Program Requirements
MVD	Model View Definition
NBIMS	National BIM Standards
NIBS	National Institute of Building Science
NIST	National Institute of Standards and Technology
ODBC	Open Database Connectivity
PDF	Portable Document Format
PHP	Hypertext Preprocessor

SQL	Structured Query Language
USGBC	United States Green Building Council
VOC	Volatile Organic Compound
WBDG	Whole Building Design Guide
WAMP	Windows, Apache, MySQL and PHP
XML	eXtensible Markup Language

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

INTEGRATE BUILDING INFORMATION MODELING AND GREEN BUILDING CERTIFICATION: THE BIM – LEED APPLICATION MODEL DEVELOPMENT

By

Wei Wu

August 2010

Chair: R. Raymond Issa
Cochair: Charles J. Kibert
Major: Design, Construction and Planning

Building information modeling (BIM) and green building are currently two major trends in the architecture, engineering and construction (AEC) industry. This research recognizes the market demand for better solutions to achieve green building certification such as LEED in the United States. It proposes a new strategy based on the integration of BIM and green building rating systems.

The research firstly conducted a feasibility survey to investigate two fundamental questions in the BIM and LEED integration: 1) what LEED certification requires; and 2) what functionality BIM possess to assist compliance with such requirements. Based on the match-up of LEED certification requirements with the functionality inventory of popular BIM software solutions, a framework was then established to prepare the theoretical foundation for pragmatic solutions to support this integration. The BIM–LEED application model was created to handle practical problems at the credit level that might occur in actual LEED projects. It consisted of two modules: “Design Assistance” and “Certification Management”. The “Design Assistance” module took advantage of the Autodesk Revit API to provide the designers with off-the-shelf LEED knowledge built

into the BIM software to ensure the design was LEED-oriented. The “Certification Management” module was a web application built upon the Apache/MySQL/PHP platform that focused on managing project information, LEED documentation and submittals for the certification purpose. Finally, the LEED Materials and Resources use case was created to preliminarily validate the application model by simulating the LEED project delivery process.

Overall, this research proposed and demonstrated that the BIM-LEED integration was feasible with considerable constraints. The integration should accommodate the needs of different team members with specialized assistance at different stage of the project delivery process. New functionalities of BIM software solutions and better support for information exchange at the database level would facilitate more rigorous implementation of BIM in green building certification.

CHAPTER 1
INTRODUCTION

The Era of New Challenges

The architecture, engineering and construction (AEC) industry has been witnessing a boom in building information modeling (BIM) used in parallel with the continuous momentum of the green building movement in the last decade or so. Although quite unrelated concepts at first glance, BIM and green building collectively are able to best address the unprecedented challenges in productivity and sustainability encountered by the AEC industry.

Teicholz (2004) noted that in contrast to the overall improvement of productivity in non-farm industries, productivity in the construction industry had actually regressed between 1964 and 2003. Teicholz accounted for this abnormality by identifying the following major causes:

- A significant portion of the construction business process is classified as non-value adding due to the fragmentation of existing business paradigm, and
- Lack of interoperability in heterogeneous applications of information technology across the industry has exacerbated the situation.

Statistics from a 2004 National Institute of Standards and Technology (NIST) research report have confirmed the magnitude of the interoperability issue by providing that the failure to adequately support industry information exchange costs as much as $15.8 billion yearly (Gallaher et al. 2004).

On the other hand, the far-reaching adverse impacts of the AEC industry on the natural environment have been well documented with the increased public awareness of such impacts. According to the U.S. Green Building Council (USGBC 2009), in the United States buildings alone account for:

- 72% of electricity consumption,
- 39% of primary energy use, including fuel input for production,
- 38% of all carbon dioxide (CO_2) emissions,
- 40% of raw materials use,
- 30% of waste output (136 million tons annually), and
- 14% or 15 trillion gallons of potable water consumption.

The business-as-usual paradigm that views the environment as an infinite source of materials and energy and a repository for waste is no longer effective to help the industry tackle the challenges posed by the dual demands of increasing the productivity and mitigating the environmental impacts of the built environment. New paradigms have been proposed, highlighting the roles of smarter IT applications such as BIM, and more environmentally-conscious practice exemplified by green building design and construction. This research takes one step further to look at the synergy between BIM and sustainability, and seeks a truly integrated business paradigm of the AEC industry in an era of new challenges.

Basics of BIM

BIM started to gain popularity at the turn of the new millennium however BIM as a technology is not new to the industry. Terms like building product model, virtual building and intelligent object model have been in use for over twenty years, and they could be perceived as earlier forms of BIM. The development of both the concept and the technology of BIM is contextual and user specific (Eastman et al. 2008). However, it is most important to understand that BIM is not about a simple 3D geometric model or a specific software application. This has been a major misconception in the industry. Jernigan (2007) pointed out that there were two basic formats one could rely on to avoid confusion about building information modeling. The “little bim” is used to represent applications-focused topics, for instance, software packages such as Autodesk® Revit®

(hereinafter referred as Revit), ArchiCAD®, and Bentley® are "bim" tools. The "BIG BIM" is the management of information and the complex relationships between the social and technical resources that represent the complexity, collaboration, and interrelationships of today's organizations and environment. The focus is on managing projects to get the information to the right place at the right time.

To help clarify what BIM is, a consistent and official definition of BIM is surely needed. Various versions of this definition have been proposed around the world. In the United States, the National Institute of Building Science (NIBS) is one of the leading organizations that conduct research in BIM. They provided the following definition in the first release of the National BIM Standard:

> A BIM is a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward. A basic premise of BIM is collaboration by different stakeholders at different phases of the lifecycle of a facility to insert, extract, update, or modify information in the BIM to support and reflect the roles of that stakeholder. The BIM is a shared digital representation founded on open standards for interoperability. (NIBS 2007)

According to this definition, the content of BIM is the shared building life cycle information; its role is to support all stakeholders in decision-making at different phases with reliable project data readily captured; and the basis of such support is the freedom of information exchange empowered by open standards for interoperability.

Basics of Green Building

The term sustainability is a legacy of the 1987 Report of the World Commission on Environment and Development (WECD): Our Common Future, which defined sustainable development as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs." Green building is the contextual implementation of general sustainability principles in the AEC industry. Those principles advocate the regulation of building activities to mitigate impacts on climate change, energy consumption, resource depletion, water conservation, land degradation and biodiversity, to name a few. They also set up a baseline performance for the built environment and promote improvement in indoor environmental quality to promote occupants' health and productivity. The final products of practicing sustainability in the AEC industry will be green buildings.

In order to efficiently guide the design and construction of green buildings, it is beneficial to have consistent metrics for the quantitative and qualitative evaluation of building performance. These systematic portfolios of metrics are usually known as the "green building rating systems". Fowler and Rauch (2006) defined green building rating systems as "tools that examine the performance or expected performance of a 'whole building', translating this into an assessment scheme for comparison with other buildings." In the business case, as the demand for more sustainable properties rises up steadily, building owners and developers perceive building green as more than a challenge but rather a promising profit source, as confirmed by the gradual acceptance of green building rating systems in the industry. With recent governmental endorsement and incentives, the green building market has been rejuvenated, making pursuit of certified green buildings become a huge momentum in the market transformation. Currently, the Leadership for Energy and Environmental Design (LEED) is one of the most popular green building rating systems in the United States. LEED certification also becomes a thriving business in global green building market.

Other popular systems around the world include BREEAM from the UK, CASBEE from Japan, Green Globes U.S. (adapted from Green Globes Canada), and SB Tool (formerly known as GB Tool, Canada). A quick review reveals that the general structure of these rating systems includes (but is not limited to):

- **Assessment targets:** building performance and functionality vary significantly according to their types (e.g. office, retailing, residential and school), and stages of their life cycle (e.g. new construction, operation and maintenance). A rating system needs to be specific on which type(s) of buildings it is evaluating and certifying. For instance, the current LEED family includes rating systems of LEED-NC (new construction); LEED-EB (existing building); LEED-O&M (operation and maintenance); LEED-CS (core and shell); LEED-CI (commercial interior); and LEED-H (homes);

- **Assessment categories:** the assessment categories (often termed “credits”) address the contents and dimensions encapsulated in the green building design and construction (e.g. energy, water, materials, community and occupant health); set up corresponding performance requirements and metrics; and provide guidelines for compliance;

- **Scoring system:** the weighted scores calibrate the performance of buildings; determine the status of compliance; and cascade the certification awarding tiers; and

- **Documentation requirements:** comprehensive documentation is required to facilitate communication; support claim for credit compliance; certification review and award.

BIM for Sustainability: the Initiatives

When looking into the paradigm shift in the green building movement and the transition to building information modeling, professionals with dual expertise tend to think about possible synergies between them. It makes better sense when breaking down the project delivery of a green building. For instance, most mainstream BIM authoring tools today have built-in functionalities needed to configure building performance through simulation (e.g. energy, daylighting and thermal comfort). So at the very beginning of the project delivery, the owner and the project team will be able to embark on sustainability assessment. Later on, with all design information stored in a centralized and integrative building information model, the project team will have a reliable data resource to facilitate that all sustainability goals will be realized in the construction process, passed on to facility operation and maintenance and eventually to facility deconstruction. Because of the flexibility of information exchange, the stakeholders can continuously update the BIM to monitor and manage the building performance. In such a manner, the building is truly green and sustainable from a life cycle perspective.

At this moment, substantial attempts to integrate building information modeling with sustainability have been championed by software companies including Autodesk, Graphisoft, Bentley and Digital Project. Autodesk as far back as 2005 published a whitepaper on “Building Information Modeling for Sustainable Design,” and similar initiatives have been instituted by other abovementioned companies. Meanwhile, in academia efforts have been undertaken with emphasis on technological support of this integration established on the empirical evidence from successful case studies in the industry.

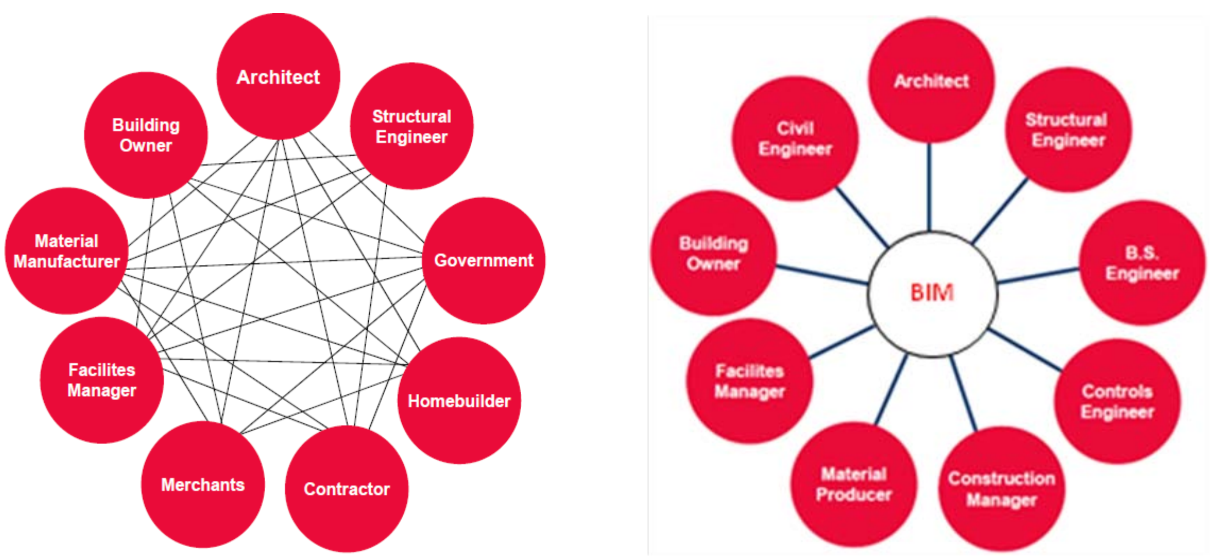
A possible approach to boost BIM application in sustainability is to create the integration of green building rating systems into current BIM authoring software. This will help project teams make more informed decisions at the early design stage to accommodate sustainability goals, and potentially generate the optimum impacts with the least cost. As soon as construction starts, the sustainability-embedded building information model evolves with newly generated field data and updates to maintain the project’s focus on sustainability. More importantly, developers nowadays typically would like to be acknowledged for “building green”, for instance, obtaining LEED certification for their projects. Integrating the green building rating system with the building information model, will give that project a better chance to achieve the desired certification.

BIM for Green Building Certification: a First Glance

Compared with traditional CAD applications, BIM stands out with its intelligence enabled by object-based parametric modeling. According to Eastman et al. (2008) such intelligence typically includes:

- **Conflict detection:** 3D parametric modeling systems will take into account spatial interferences between objects and automatically update the layout to avoid them, if relevant rules have been predefined and embedded in them;
- **Topological structures:** topological connections answer questions like what can be connected; what the connection consists of; and how the connection is composed in response to various contexts. Topology and connections are critical aspects of BIM tools that specify what kind of relations can be defined in rules;
- **Property and attribute handling:** properties and attributes of objects supplement information other than geometry or topology, but provide useful data for objects to be analyzed, priced, and procured by other applications. These are critical information needed in the real world project delivery process and are missing in current 2D based practice. Current BIM authoring tools default to a minimal set of properties for most objects and provide the capability of adding extendable sets; and
- **Consistent drawing/documentation generation:** with BIM, each building object instance-its shape, properties, and placement in the model-is defined only once, and because of the non-redundant building representation, all drawings, reports and analysis datasets are consistent. This capability alone resolves a significant source of errors and guarantees internal consistency within a drawing set.

For professionals participating in green building projects, these features are highly valuable. In order to fulfill the requirements of green building rating systems such as LEED, documenting the building information is the key being successful. Figure 1-1A describes the current industry complexity of information generation and exchange among project team members. A major drawback in this paradigm is due to the lack of a centralized information source for the project. This fragmentation and inconsistency make this process error-prone, and the redundancy causes loss of efficiency, cost overrun, or even potential failure of the project delivery. In contrast, a fully developed BIM model synthesizes the full range of project information as shown in Figure 1-1B. Conceivably this model will also capture the particular information required for green building certification in addition to providing better-quality construction documents. More importantly, with this highly integrative model, project team members can access the model and extract information from a single reliable source. Such a BIM (information)-centric paradigm consistently keeps the whole project team on the same page, and significantly reduces change orders or rework due to erroneous project information. As expected a process relying on this paradigm will raise the profitability of green building projects and eventually increase the chances of accomplishing the desired level of green building certification.



A) Documentation-centric model. B) Information-centric model.

Figure 1-1. Project delivery paradigm shift. (Source: Sjøgren 2007).

Given that fact that very few green projects today have BIM involved, professionals especially experts in BIM and green buildings see the impacts of BIM increasing on the horizon. As a matter of fact, according to the most recent SmartMarket Report published by McGraw-Hill Construction (2009), North American AEC professionals believes that BIM will be highly valuable in producing better-performing buildings, and expect high increase in use of BIM on LEED projects (Figure 1-2) in the North American building market.

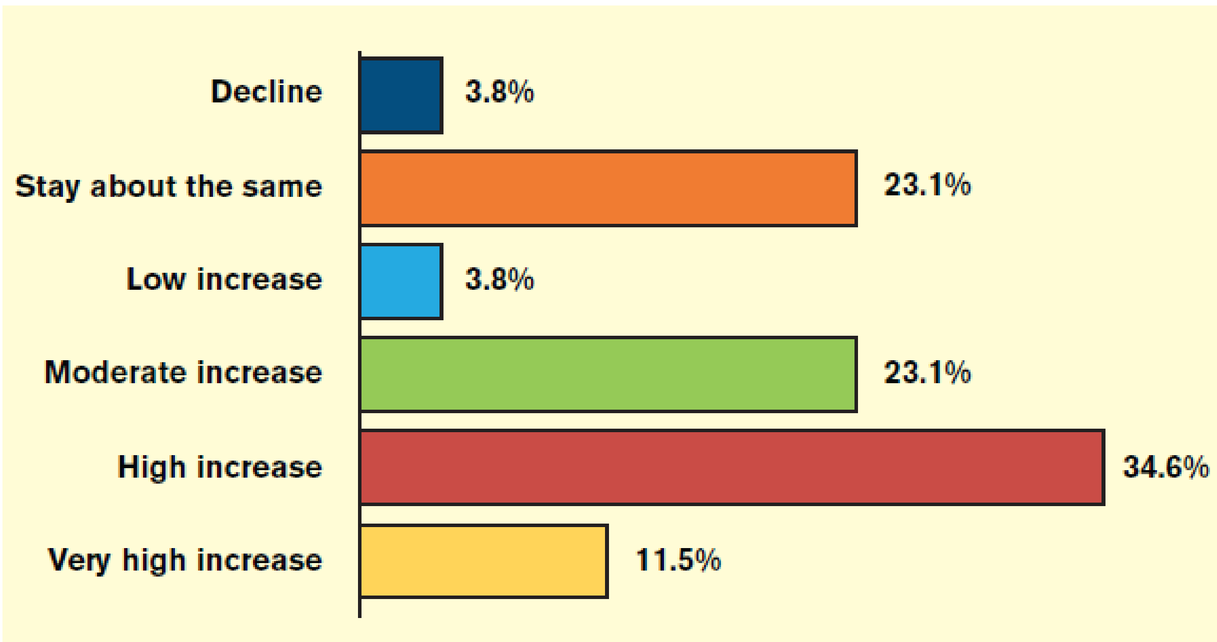


Figure 1-2. Expected growth in BIM use on LEED projects. (Source: McGraw-Hill Construction 2009).

CHAPTER 2
RESEARCH SCOPE

Identifying the Problem

In the North American building market, a very meaningful case for the BIM and green building integration to look at will be the implementation of BIM in the LEED certification process. Due to governmental endorsement and strong marketing of the U.S. Green Building Council (USGBC), LEED certification has become a thriving business paradigm in promoting sustainability in the AEC industry. The debate over LEED on whether it is a scientific system continues, but professionals do acknowledge its positive impacts on leading the industry's transition to green. In light of the LEED system, USGBC along with ANSI, ASHRAE and IES has published a new standard that defines the minimum requirements for a high-performance green building. The ANSI/ASHRAE/USGBC/IES Standard 189.1-2009 for the Design of High-Performance Green Buildings except Low-Rise Residential Buildings recently became a jurisdictional compliance option in the Public Version 1.0 of the International Green Construction Code published by the International Code Council. The IGCC regulates construction of new and remodeled commercial buildings, and Standard 189.1 serves as a technical backbone of it (ASHRAE 2010). In addition, many corporate investors perceive the pursuit for LEED certification for their assets as a public relation move to set their business apart from competitors in the market.

The challenge to achieve LEED certification is well acknowledged in terms of the technology intensity, extra costs and cumbersome documentation management. Experience is indisputably critical given the fact that the LEED rating system is not fully written in plain language. Project teams often find it difficult to understand what exactly

USGBC requires for a specific credit, and end up having to file a CIR (credit interpretation request) to find out. Such requests are always associated with a nontrivial cost, exacerbating the already tightened budget in today's market. Even worse is the documentation part. As introduced in the overview of green building rating systems, LEED has a credit/point structure and carries a scoring system to evaluate a building's performance in determining its compliance with these credits' requirements. Basically, other than actual field inspection, the official review of USGBC is mostly paperwork based. The project team has to submit a considerable amount of documents in a strictly controlled format (LEED templates) through a special system (called LEED-Online) administered by the USGBC. Apparently, the quality of the documentation and the ease of generating the required LEED documentation are of direct interest and critical importance to the success of a LEED project.

With the LEED certification having been practiced in the market for over a decade, project teams have gained substantial experience to deal with USGBC and the LEED system. Creative strategies have been thought out to improve productivity in the LEED project delivery. Noticeably, the peripheral businesses that provide services to LEED documentation management are booming at the same time. Outsourcing the documentation part to those 3rd party solution providers becomes quite popular. Nonetheless, this outsourcing approach might prove to be problematic. A major concern here is on the integrity of project information in communication between the project team and the contracted 3rd party documentation agent. By involving extra personnel and introducing more fragmentation into the LEED process, chances of making even more mistakes in data collection and documentation preparation are simply higher.

Unfortunately, in fear of the tedious process of compiling the required LEED documentation, more than a few project teams have opted to take the risks anyway and try to make certain tradeoffs in profitability afterwards.

The advent of BIM technology, especially with anecdotal evidence of its implementation in green projects spreading in the industry, has caused professionals to start envisioning the integration of BIM and LEED certification process. According to Eastman et al. (2008), 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 LEED project delivery, for instance, dealing with the complexity of conducting full building energy simulation, acoustical analysis, and daylighting design. The scenario that project teams can click some magical BIM button and will be able to comply with all pursued LEED points meanwhile accomplish all dreary tasks of compiling the LEED project documentation is not yet realistic at this moment.

In regards to leverage a green building project delivery with BIM, particularly when the eventual goal is to achieve a certain credential such as LEED certification, some of most critical outstanding issues will include:

- How to interpret the requirements of the rating system (at the credit level) into requests for data;
- What desirable functionalities BIM applications should possess to generate the requested data;
- What-if scenario when the desired functionalities are not yet available; and
- How to facilitate project management using BIM and green building integration.

When studying the North American building market, the rating system in the above list has to be the LEED green building rating system, and the major BIM application software will be Revit from Autodesk based on market share statistics (McGraw-Hill Construction 2008).

Scope of Research

This research attempts to look at the integration of BIM and green building from a systematic perspective, using the LEED rating system and the LEED certification as a unique case. An important assumption for this research is that there is a market trend to adopt BIM in the green building delivery and certification process. In response to the problems as identified in previous paragraph, it is the primary objective of this study to propose a solution to those issues:

- **Objective I:** Investigate the feasibility of the full scope integration of BIM and LEED rating system;
- **Objective II:** Create and develop the generic framework for this integration based on the matchup of the prescribed LEED credits requirements and the functionality of Revit;
- **Objective III:** Identify the gaps in the framework where no existing functionality is available to help compliance with certain LEED credits, demonstrate development of functionality extensions through the application programming interface (API), and make constructive recommendations;
- **Objective IV:** Look into the project management aspect of this integration, and provide an applicable solution to LEED certification with emphasis on documentation compiling and management; and
- **Objective V:** Develop the BIM – LEED application model and preliminarily validate it through the use case of Materials and Resources category.

Research Significance

The AEC industry is in the midst of transition to a new business paradigm, green building and BIM will continue to be the hotspots during this paradigm shift. As new technology emerges and is updated almost on a daily basis, the expectation from clients on building projects balloons simultaneously. The demand for high performance buildings will predictably ascend as more public and private investment pours into the market.

To tackle those challenges, integrating BIM and green building needs to be pursued. The fundamental contribution of this research will be the unique approach it proposes to fulfill green building certification such as LEED by integrating functionalities of BIM. It conducted a comprehensive literature review (Chapter 3) to explore the theoretical foundation, and created a comprehensive integration framework to guide and foster practical innovation. It demonstrated the integration by looking at the most popular green building rating system: LEED and the most prevailing BIM software: Autodesk Revit. The information-centric project management solution illustrates an optimized workflow in LEED certification that outperforms conventional approaches. As a whole, the BIM-LEED application model makes an ambitious effort to provide professionals with an off-the-shelf tool to facilitate the actual LEED project delivery process (Chapter 5). With further validation and improvement, the application model could be developed into a real product to be used by LEED project teams. Recommendations (Chapter 6) were also made to future research that could contribute to the steady advancement in BIM and green building integration.

CHAPTER 3
LITERATURE REVIEW

Overview

This chapter reviews the literature in relation to the primary research objectives. An analysis of the rationales inside the green building rating systems helps interpret the data requirements embedded in the prescribed rating criteria (requirements). A close look at current major BIM solutions summarizes the inventory of available functionalities to support sustainability. Analysis of the empirical evidence of BIM applications in green building projects fosters the assumption in pursuit of the integration. The undergoing endeavors in the integration framework will provide reference to more intensive development for the use case in BIM and LEED integration.

Rationale in Green Building Rating System

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 construction industry and the built environment are key areas if human beings are to attain a sustainable development of societies as stated in CIB Agenda 21 on sustainable construction (CIB 1999). According to the UNEP's vision (2006) for sustainability in the building and construction sector:

- Buildings are routinely designed and maintained to be optimized over their entire life span;
- 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 active role in encouraging sustainable building and construction practice.

Most of current green building rating systems are not formal standards or building codes. They are consensus based voluntary programs, and sometimes professionals have conservative opinions about them for lack of scientific foundations. For instance, despite of the prevalence of LEED in the U.S., it has been criticized for unjustified weighting of points allocated to each environmental category by many professionals in the AEC industry. Udall and Schendler (2005) developed a comprehensive critique of the defects and flaws of LEED in guiding green building development. Recent revision of LEED has reflected dedication to resolving such problems. A step further is that some green building standards have been developed on the basis of these green building rating systems, for instance, the ANSI/ASHRAE/USGBC/IES Standard 189.1-2009 (ASHRAE 2010) based on LEED and the ANSI/GBI 01-2010 (ANSI 2010) based on the Green Globes.

The scope of the sustainability framework is enormous. In the context of the AEC industry alone, the immensity of issues that should be addressed to efficiently promote sustainability in the built environment seems overwhelming. Carefully adopting the criteria to guide green building design and construction is thus an ongoing task for all stakeholders in the industry.

Sustainability Indicators

Sustainability indicators integrate environmental, social, and economic factors so that the complex cause and effect relationships between these multiple factors can be more readily investigated (Guy and Kibert 1998). Indicators are needed to precisely define sustainability criteria and to measure the performance of the construction industry and the built environment. Decision-makers and policy-makers need indicators to evaluate economically viable and technically feasible strategies to improve the quality of life, while at the same time increasing resource use efficiency. Numerous actors in the construction and development process need tools and guidelines based on indicators to improve current practices and the quality of construction (CRISP 2002). Agenda 21, Chapter 40 states that "Indicators of sustainable development need to be developed to provide solid bases for decision making at all levels, and to contribute to a self-regulating sustainability of integrated environmental and development systems" (CIB 1999). Hence the development of sustainability indicators should follow criteria such as:

- Relevance: clear link to a goal and an objective of sustainability;
- Objectivity: based on reliable information;
- Accessibility: appropriate data exist and are accessible;
- Readability: understandable for a project team and community;
- Measurability: quantifiable data extraction and interpretation; and
- Sensibility/Responsiveness: fast and efficient track of changes (Guy and Kibert 1998).

The dedication to the identification and creation of scientific sustainability indicators has become a global phenomenon. The International Organization for Standardization (ISO 2006) published the pilot technical specification: ISO/TS 21929-1, Sustainability in Building Construction – Sustainability Indicators – Part 1: Framework for the Development of Indicators for Buildings, in order to standardize the process of defining a framework for sustainability indicators of buildings, and give guidelines for the development and selection of sustainability indicators related to buildings.

The European Commission launched a comprehensive research project named CRISP: A European Thematic Network on Construction and City Related Sustainability Indicators in 1999 as a 3-year network gathering 24 members from 16 countries, dealing with Construction and City Related Sustainability Indicators. It brought together the work of a carefully selected set of 24 skilled teams that brought to the network the results achieved in a wide range of national and international projects in this field from across the breadth of Europe. The major deliverables of this project included:

- The national state-of-the-art reports;
- The collection of recent and on-going R&D works in different countries;
- The CRISP indicator database (available at http://crisp.cstb.fr/database.asp);
- The public Website (http://crisp.cstb.fr) gathering all these elements (CRISP 2002).

The CRISP project also defined the role of sustainability indicators in the general sustainability framework (see Table 3-1), especially under circumstances when these indicators were used in combination at the regional or project level, which is exactly how a green building rating system such as LEED was executed.

Table 3-1. Role and position of indicators in general sustainability framework (Source: Adapted from CRISP 2002)

Definition	Description	Sample Value
Goal ⇩	A broad statement that defines the ultimate condition desired	Maximize the diversion of all waste from disposal
Objective ⇩	A desired direction of change	Reduce the generation of solid waste at source
Indicator ⇩	A variable which helps to measure a state or a progress towards an objective	Per capita disposal (kg/person/year)
Performance Target ⇩	A desired level of performance	200kg/person/year
Tool	A pertinent use of several indicators and performance targets in relation to local conditions and specific uses	LEED/BREEAM

In the U.S. market, Guy and Kibert (1998) reviewed the experience in developing indicators of sustainability, and discussed the two major frameworks being used for sustainable efforts at the community level: Local Agenda 21 and the Healthy Communities Initiative. Kibert (1994) also inspected the concept of sustainable construction – a term often juxtaposed with green building – and defined it as “the design and operation of a healthy built environment based on resource efficiency and ecological principles”. Kibert and Guy (1998) also made the pioneering efforts in proposing methods for the development and selection of indicators for sustainable construction (Table 3-2), and commented that:

> Indicators of sustainable construction consider linkages to the greater community while addressing the specific issues of planning, architecture, construction operations, operation and building reuse and adaptation, and final disposal…Best practices of indicators selection use a combination of environmental, economic, and social factors in an integrative fashion. Critical indications of sustainable construction will focus on issues such as diversity and density of land use including urban agriculture, and functioning urban natural ecosystems. (Kibert and Guy 1998)

Table 3-2. Indicators of sustainability in construction (Source: Guy and Kibert 1998)

Land	Water	Materials	Energy Use	Toxins
“Brownfield” land developed annually as a percent of identified sites	Total impervious surface and/or impervious surface area per unit area	Tons of C&D waste recycled per unit area of new construction	Automobile accidents per selected intersections	Smoke-free interior environments as percent of total construction
Area of green space per building square feet	Per capita water consumption	Number of historic structures	Percent of total electricity consumption from renewable resources	
Inventory of tree cover	Consumption of recycled / reclaimed water per capita	Percent of commercial buildings with in-house recycling		
Ratio of land area to perimeter distance of the municipality				

LEED as the Sustainability Indicator Tool

LEED or other equivalent green building rating systems encompass a collection of sustainability indicators to holistically assess 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. 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. This research is focused on the North American market, thus the sustainability indicators used by the LEED rating system is of immediate importance to this research.

LEED is a third-party certification program and a nationally accepted benchmark for the design, construction and operation of high performance green buildings. 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 (Figure 3-1), and kept evolving over time. The current version is LEED v3.0, which consists of three major parts:

- LEED 2009 version of all rating systems, including New Construction, Core and Shell, Commercial Interior, and Schools, 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).

LEED has two key fundamental attributes. First it was developed with an open consensus–based process, with input from a broad range of building industry professionals and other experts, including the U.S. Department of Energy. Second and common to the other rating systems, using LEED is voluntary. 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 and Nies 2008).

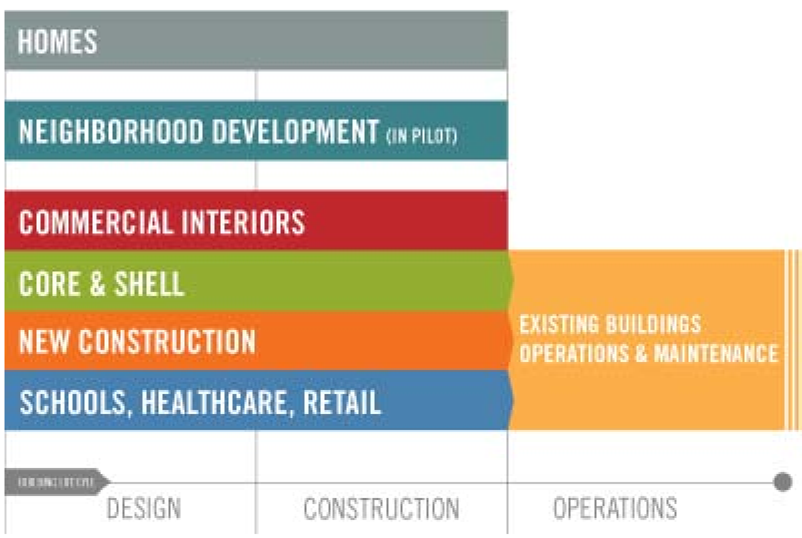


Figure 3-1. LEED rating systems. (Source: USGBC 2008).

According to USGBC (2008), “LEED is intended to provide building owners and operators with a concise framework for identifying and implementing practical and measurable green building design, construction, operations and maintenance solutions, using strategies aimed at improving performance across all the metrics that matter most: energy savings, water efficiency, CO_2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts". Taking LEED-NC 2009 for example, under this rating system, buildings are evaluated against five major environmental categories. An additional category, Innovation in Design, addresses sustainable building expertise as well as design measures not covered under the five environmental categories. Regional bonus points are another feature of LEED and acknowledge the importance of local conditions in determining best environmental design and construction practices. An overview of these categories is listed below:

- Sustainable Sites (SS, 1 prerequisite, 8 credits, 26 points)
- Water Efficiency (WE, 1 prerequisite, 3 credits, 10 points)
- Energy and Atmosphere (EA, 3 prerequisites, 6 credits, 35 points)
- Material and Resources (MR, 1 prerequisite, 7 credits, 14 points)
- Indoor Environmental Quality (IEQ, 2 prerequisites, 8 credits, 15 points)
- Innovation in Design (ID, 0 prerequisite, 2 credits, 6 points) and
- Regional Priority (RP, 0 prerequisite, 1 credit, 4 points)

In order to get LEED certified, the project has to satisfy the minimum program requirements (MPR, effective from the LEED v3), all the prerequisites and a minimum of 40 points. If the project goes beyond 40 points, it will be certified as Silver (when achieving 50-59 points), Gold (when achieving 60-79 points) or Platinum (when achieving 80+ points). A step-by-step guide for the project certification is available at the GBCI's website (http://www.usgbc.org/DisplayPage.aspx?CMSPageID=64).

To determine if the project meets these credits' requirements, and how many points the project has actually attained, USGBC requires comprehensive documentation for review. The documentation includes two major parts:

- **Compulsory documentation:** this includes the official LEED Online templates created specifically for each LEED credit, and other critical project submittals that apply to any building project delivery. The project team has to fill the LEED templates and submit them through LEED Online.

- **Supplemental documentation:** this includes any other materials that the project might feel helpful to achieve a certain point. Typically this type of documentation is submitted as attachments to the compulsory documentation.

USGBC seldom conducts field inspection to verify the documentation submitted by the project teams due to their belief in professional ethics. This makes the quality and comprehensiveness of the submitted documentation very important for the project team to achieve the targeted points. By carefully reviewing the credit requirements prescribed in the official guidelines (called LEED reference guide, each rating system has its corresponding reference guide compiled by USGBC and project teams have to purchase them), the project team works extremely hard to probe and prepare the information that would fit into the criteria of the reviewers from GBCI.

With the LEED Online templates, it should be straightforward for the project team to know what information and data they should provide to USGBC. The real challenge is how to obtain the information and data. Traditional project documenting methodology might still apply, but chances are that the specific LEED requirements need extra treatment that goes beyond the scope. A simple example will be meeting the requirements of Materials and Resources Credit 4: Recycled Content (MRc4, this type of abbreviation is accepted in the industry, and will be used hereinafter in this dissertation. To display credits in other categories, simply change the MR to SS or WE, etc. The letter “c” stands for “Credit”. When the letter “p” is used, it stands for “Prerequisite”). In order to achieve MRc4, the project team needs to demonstrate that a certain percentage of the materials used in the project are recycled. Extra work will be needed to keep a record of all the materials that have recycled contents, using the formula provided by the reference guide to compute the dollar value, and finally to come up with the actual percentage of the total material costs. Some of the LEED credits are cumbersome to achieve. Conceivably, this significantly increases the overhead associated with the project budget, and potentially it will hurt the project's profitability.

To overcome these barriers, the project team needs both experience and tools to accurately interpret the LEED credit requirements and understand what data to collect to show compliance with these requirements. The efficiency of generating, collecting, processing and verifying the desirable information is at the heart of the successful delivery of a LEED project. BIM implementation can substantially facilitate this process.

BIM Solution and Functionality Inventory

There are two major types of BIM solutions in the market, depending on the functionality and intended application environment. One is called BIM authoring solution and the other, BIM auditing/analysis solution. The BIM authoring tools are often large and robust applications mostly used by design firms to create and compile most of the information contained in a building information model. While the BIM auditing and analysis tools are typically designed to specialize in particular areas, and used by either design firms or contractors to perform energy analysis, sustainable design analysis, code compliance, construction cost estimate, constructability analysis and construction sequencing (Smith and Tardif 2009).

The functional and performance capabilities of different BIM solutions (termed as Functionality Inventory in this research) are relative and contextual since there is no single platform that will be ideal for all types of projects. Table 3-3 lists some of the most popular solutions in the current market, according to McGraw-Hill Construction (2008). Beyond the popularity factor, companies should base their decision-making process of what BIM software solution to procure on their business needs, company core competence, project type, budget and IT sophistication level. Smith and Tardif (2009) insightfully pointed out that the selection of the most appropriate software solutions for individual firms should be based on one criterion and one criterion alone: to enhance the revenue-generating potential of the company. This requires the decision-makers to take a renewed investment-based view, instead of the traditional cost-based view, of technology such as BIM. The advantage of an investment-based view stems from the realization that the real value of BIM to any organization laying in leveraging the structured information contained in a building information model to create value.

Table 3-3. Quick overview of popular BIM software solutions in current market (Source: Eastman et al. 2008; Smith and Tardif 2009)

Features	Revit®	Bentley®	Vico®	ArchiCAD®
Solution Type	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 bi-directional 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 user 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

Revit as the BIM Solution

In the U.S. market, the Autodesk Revit (hereinafter referred to as Revit) suite (including Revit Architecture, Structure and MEP) is the most prevailing BIM solution. Before Autodesk acquired Revit, their market-leading product AutoCAD was the most successful CAD application in the world. Revit is the specialized solution for the BIM era. Meanwhile, through research and development, partnership and continuous buyout, Autodesk currently provides a portfolio of highly integrated BIM solutions to the AEC industry, including software applications in addition to Revit, such as EcoTect (conceptual energy simulation, lighting and daylighting design, acoustical simulation), Autodesk 3ds Max (visual design), Green Building Studio (energy simulation, water consumption design and LEED daylighting design) and Navisworks (clash detection, constructability analysis, sequencing). The dominance of Autodesk products has driven the development of peripheral applications on the common Autodesk platform to proliferate. To some extent, the centralization of BIM solutions may contribute to improving the interoperability in a firms' business operation. Other software vendors such as ArchiCAD, Bentley and Vico all have loyal customers, mostly due to the particular feature preferences they have for those applications.

For the purpose of this research, Revit is selected as the core BIM solution tool, supported by supplementary in house software applications from Autodesk. Major considerations contributing to the decision to select Revit include:

- **Availability to academia:** Revit is free to academia offered by Autodesk through the online Student and Educator community;
- **User Interface:** Revit uses an interface similar to AutoCAD, which is very convenient for previous Autodesk CAD users;

- **Software Support:** Autodesk hosts an enormous amount of Revit tutorials and curriculum online and gives free access to students and faculty;

- **Customer Service:** Autodesk Revit educators provide responsive feedbacks regarding technical or application questions to users, and they have comprehensive collaboration with the academia;

- **Interoperability:** Revit is IFC certified and supports IFC import/export; it also supports ODBC which enables flexible data extraction;

- **Extensibility:** Revit has numerous useful plug-ins and extensions available that fit in very well for this research, besides it has a comprehensive API guide for developers; and

- **Impacts:** Revit is a major player in the current BIM tool authoring market, and research using Revit tends to have a greater impact on the market.

Functionality Inventory of Revit

Revit as a BIM authoring tool possesses powerful functionalities to enable the creation of a comprehensive building information model consisting of the full spectrum of building systems including architectural, structural and MEP components. More importantly, every schedule, drawing sheet, 2D view, and 3D view created in the Revit environment is derived from a single foundational database, automatically coordinating changes across all facets and presentations as the project develops and evolves (Autodesk 2009). The inventory of major functionalities of Revit in terms of BIM and green building design is summarized as follows:

- **Bidirectional Associativity:** A change anywhere is a change everywhere. 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 and omissions;

- **Schedules:** Schedules provide another view of the comprehensive Autodesk Revit model. Changes to a schedule view are automatically reflected in all other views. Functionality includes associative split-schedule sections and selectable design elements via schedule views, formulas, and filtering;

- **Material Takeoff:** 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 smoothes the material quantity tracking process. As projects evolve, the Autodesk Revit Architecture parametric change engine helps ensure material takeoffs are always up to date;

- **Interoperability:** Interoperability enhancements enable users to work more efficiently with members of the extended project team. Users can export the building model or site, complete with critical metadata, to AutoCAD Civil 3D software. They can also import accurate, data-rich models from Autodesk Inventor software, efficiently speeding time to fabrication. With support for IFC, seamless information exchange between Revit and other critical software application in the project delivery could be realized; and

- **Support Sustainable Design:** Revit supports sustainable design processes from the earliest stages. It exports building information, including materials and room volumes, to the green building extensible markup language (gbXML). Energy analysis can be performed using Autodesk Green Building Studio web-based services, and building performance can be studied using Autodesk Ecotect software. Autodesk 3ds Max Design software can be used to evaluate indoor environmental quality in support of LEED IEQc8.1 (Daylight and Views) certification (Autodesk 2009).

Implementing BIM in Green Building Design and Construction

Building design and construction are systematic and dynamic. The different building systems are physically and functionally interconnected. Use of modern mechanical, electrical, plumbing (MEP) system and building automation system (BAS) has exponentially increased the complexity of the building industry. Meanwhile it stimulated the specialization of industry trades, which indirectly resulted in the fragmentation of the project delivery process. Promoting sustainability thus has to inevitably deal with these various and interdependent building systems, ideally in a holistic manner.

With the increased use of BIM, complex processes and analyses that were previously too laborious or expensive to perform have been significantly facilitated (Autodesk 2005). The implementation of BIM technology in the construction industry is comprehensive. As noted by the McGraw-Hill SmartMarket Report (2008) major players including owners, architects, engineers, and contractors have all embarked on the initiatives. Figure 3-2 shows the different level of BIM involvement per user, and Figure 3-3 shows the major modeling elements with BIM in the industry. In regard to the actual involvement in green projects, Figure 3-4 shows an overview of the commitments to sustainability per user group. The expectations, also from the current BIM users, in the development of additional analysis tools concentrated in certain areas are:

- 50% indicated that LEED calculation software integrated with BIM would be very helpful;
- 47% thought that more building product content with data about the products sustainability characteristics should be integrated into BIM tools; and
- 44% believe energy analysis software should be integrated with BIM.

To be more specific, the following sections review exemplary BIM implementation intended for sustainability in the AEC industry. Energy simulation, water, daylighting and views were major focuses of such implementation.

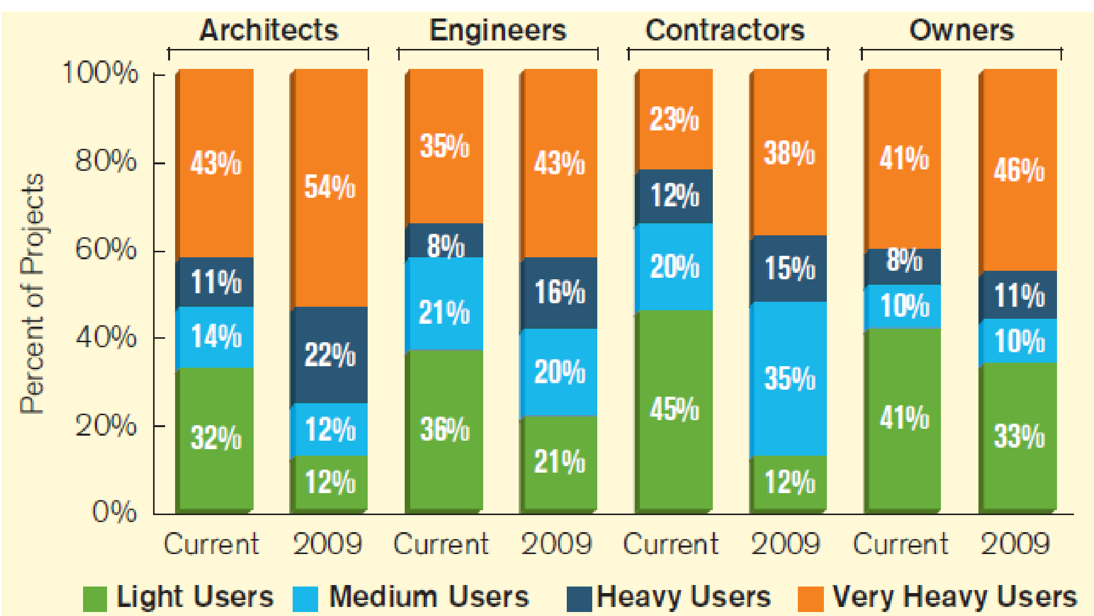


Figure 3-2. The user differences in BIM implementation. (Source: McGraw-Hill Construction 2008).

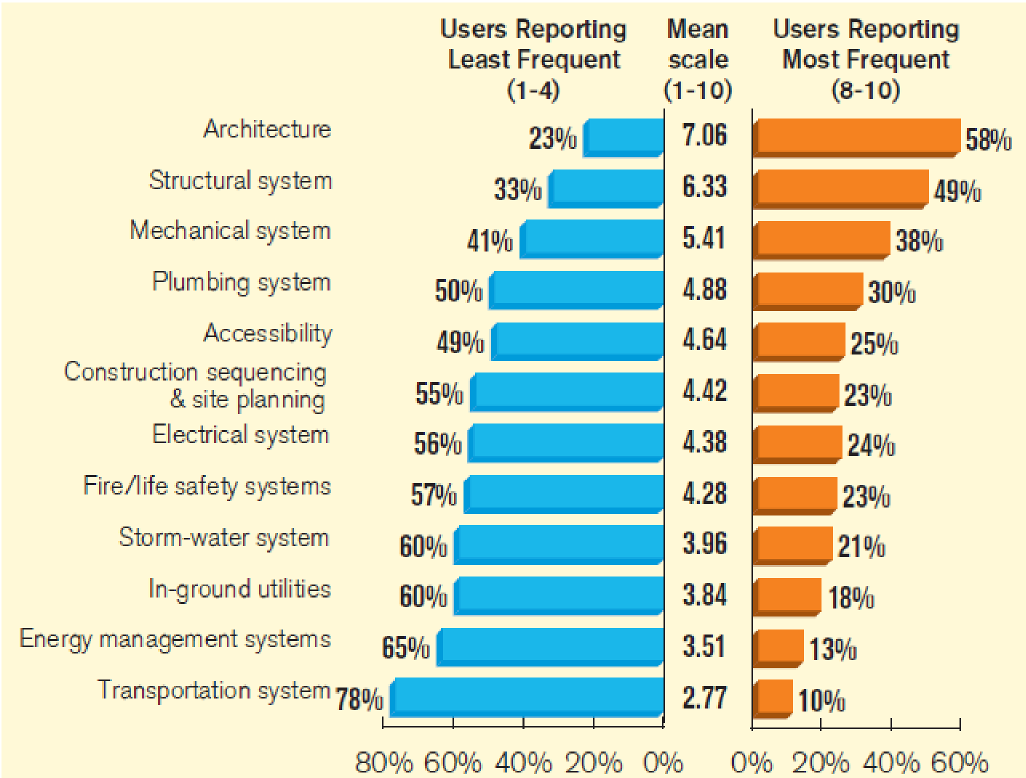


Figure 3-3. Frequency of modeling elements with BIM. (Source: McGraw-Hill Construction 2008).

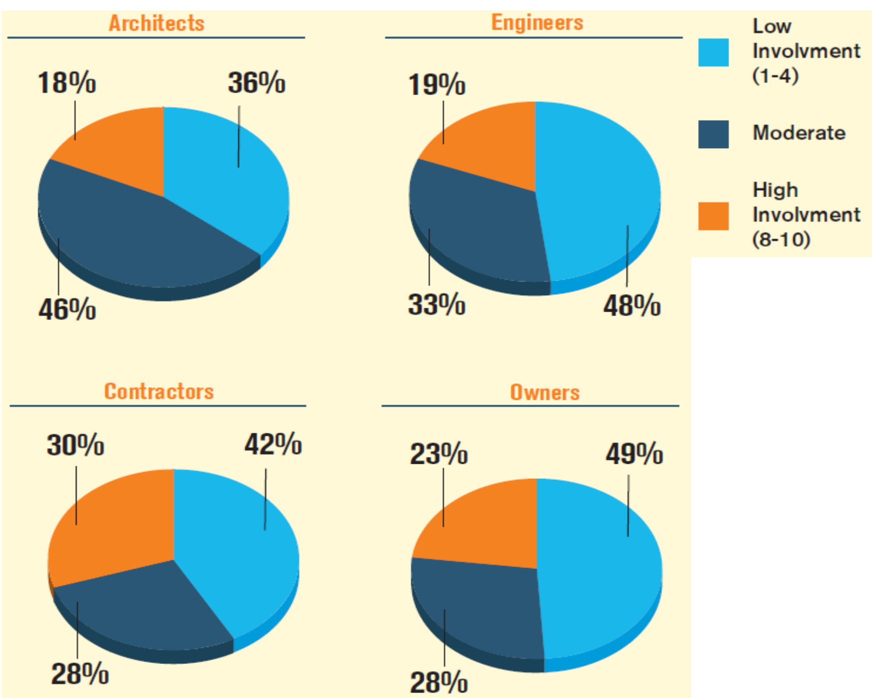


Figure 3-4. BIM use in green projects per user group. (Source: McGraw-Hill Construction 2008).

Energy Simulation in BIM

Energy simulation is an established and critical requirement in the design of sustainable buildings. Simulation tools like EnergyPlus, DOE-2, and Energy-10 were developed long before BIM's prevalence. What BIM brought to energy simulation was really 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. The adoption of BIM in the early stages of design is crucial in order to exploit its benefits (Schlueter and Thesseling 2008). As one of the first official institutions requiring BIM, the U.S. General Service Administration (GSA) leveraged BIM for the submission of mayor 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).

Newly emerged simulation tools like Integrated Environmental Solution <VE> (IES Virtual Environment) and Green Building Studio (GBS) are able to conduct comprehensive building performance analysis, including energy simulation. IES and GBS both have direct interaction with mainstream BIM authoring tools such as Revit. 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.

Energy simulation using IES<VE>/Revit plug-in

IES's specially developed Revit plug-in Toolbar (Figure 3-5) allows performance analysis and BIM within the same platform (Figure 3-6). 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. The data generated by IES' software can be used, for example, to demonstrate to the client why different design options have been chosen, quantify the energy savings expected and aid in the design of building management systems (Figure 3-7, IES 2009).

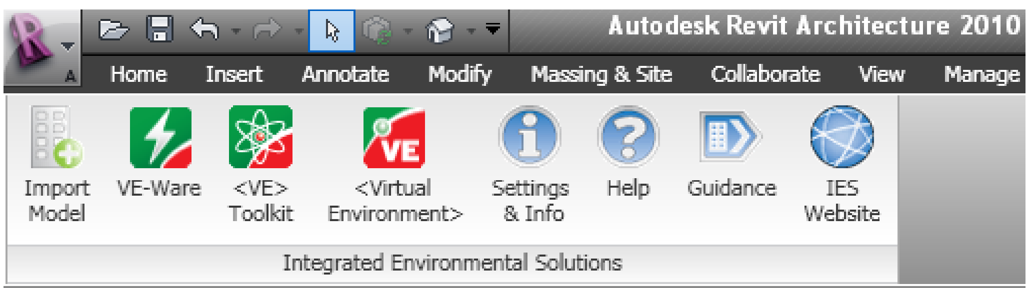


Figure 3-5. Integrative BIM and energy analysis platform. (Source: IES 2009).

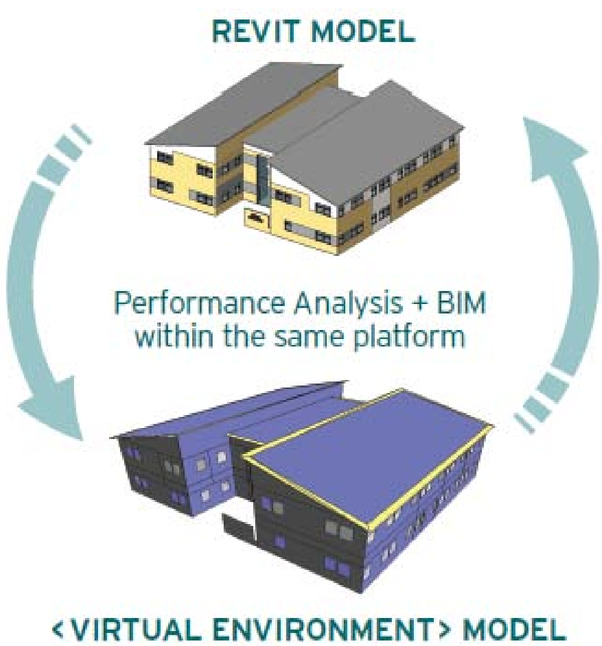


Figure 3-6. The IES<VE> plug-in interface in Revit. (Source: IES 2009).

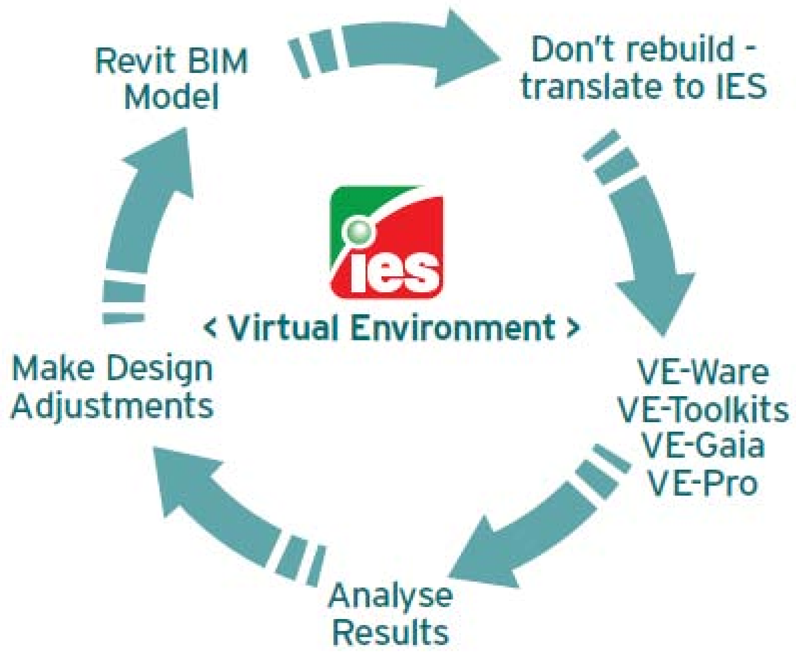


Figure 3-7. Workflow using IES<VE> with Revit. (Source: IES 2009).

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 (Figure 3-8).
- Room-based modeling is the concept of modeling and defining each Room as its own thermal zone. 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 a more accurate building performance analysis (Figure 3-9).

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. Figure 3-10 provides an excerpt of such report generated by the IES<VE> plug-in in Revit.

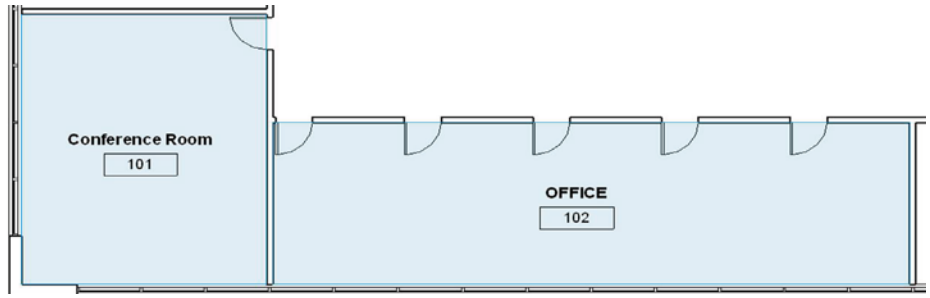


Figure 3-8. Zone-based modeling – floor plan. (Source: IES/Revit 2010).

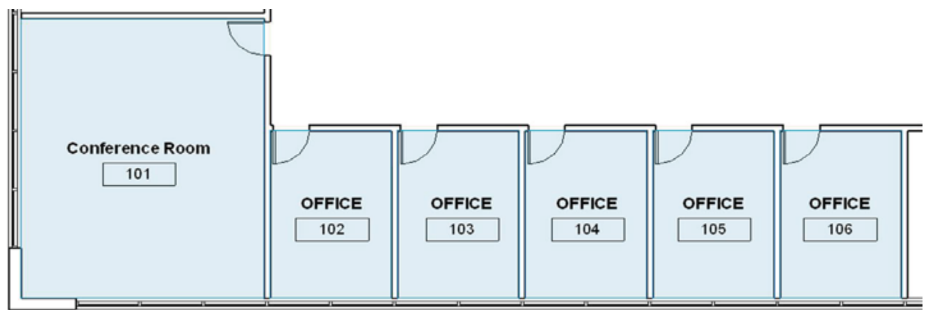


Figure 3-9. Room-based modeling – floor plan. (Source: IES/Revit 2010).

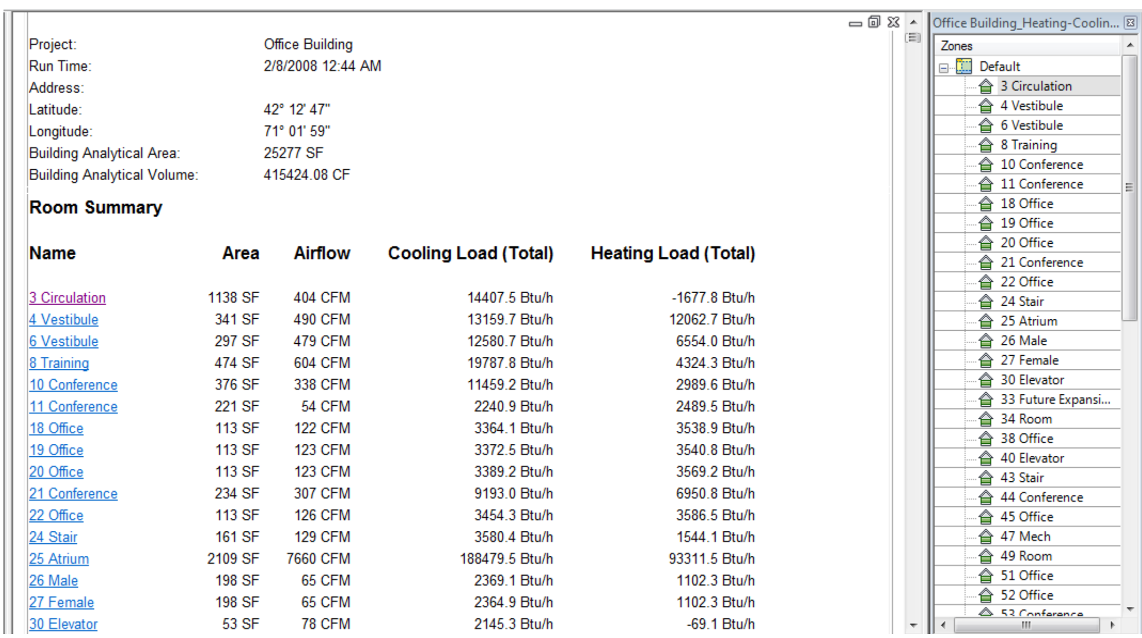


Figure 3-10. IES<VE> load calculation report in Revit. (Source: Model courtesy of Autodesk)

Energy simulation using GBS/Revit plug-in

The link between the Revit platform and the Green Building Studio web service (Autodesk 2008), now an Autodesk product, has been streamlined through a plug-in that enables registered users to access the service directly from their Revit design environment. A key step triggering the conversation between the Revit model and the GBS analysis engine requires the use of gbXML (Green Building eXtensible Markup Language). The Green Building XML schema was specially developed to facilitate the transfer of information from building information models to integrate with design/energy performance analysis (gbXML 2009). A gbXML document organizes information according to the following hierarchy: Location, Building, Space, Surface and Opening (see Figure 3-11).

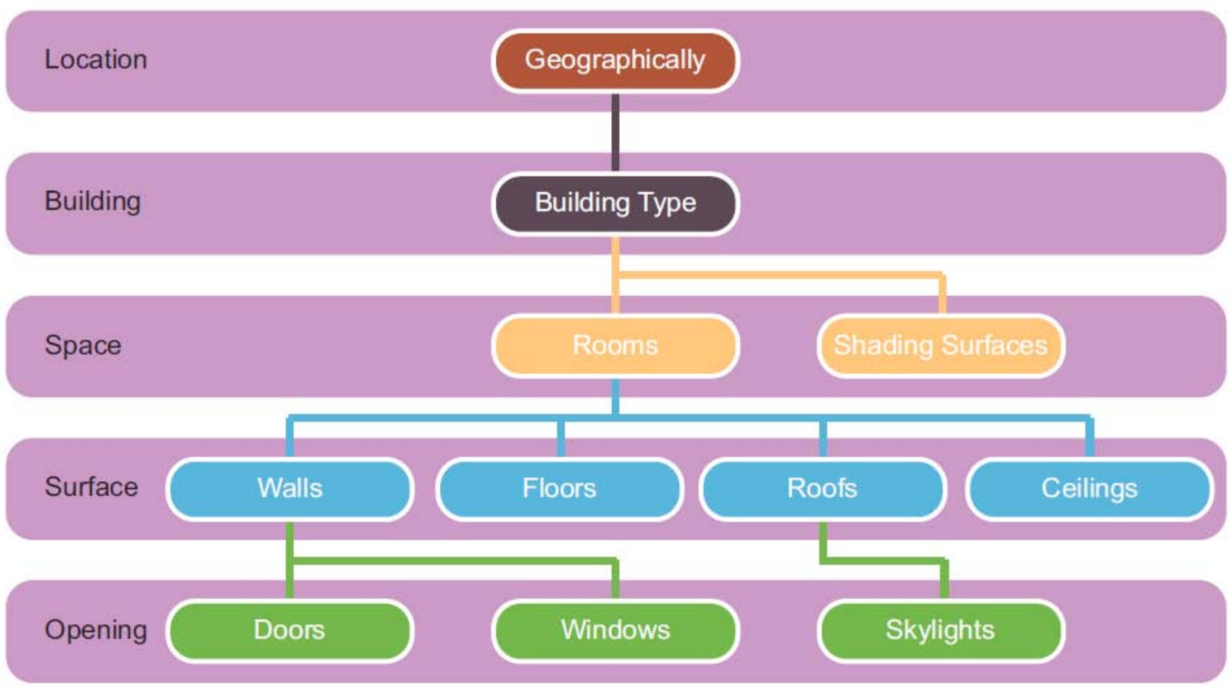


Figure 3-11. Hierarchy diagram of the gbXML schema. (Source: IES/Revit 2010).

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 (Figure 3-12). A handy function of GBS supports design alternative analysis. Using simple drop-down menus, architects can quickly change any of these settings to define specific aspects of their design; a different building orientation, a lower U-value window glazing, higher insulation wall types, or a HVAC system with higher SEER value for example (Figure 3-13).

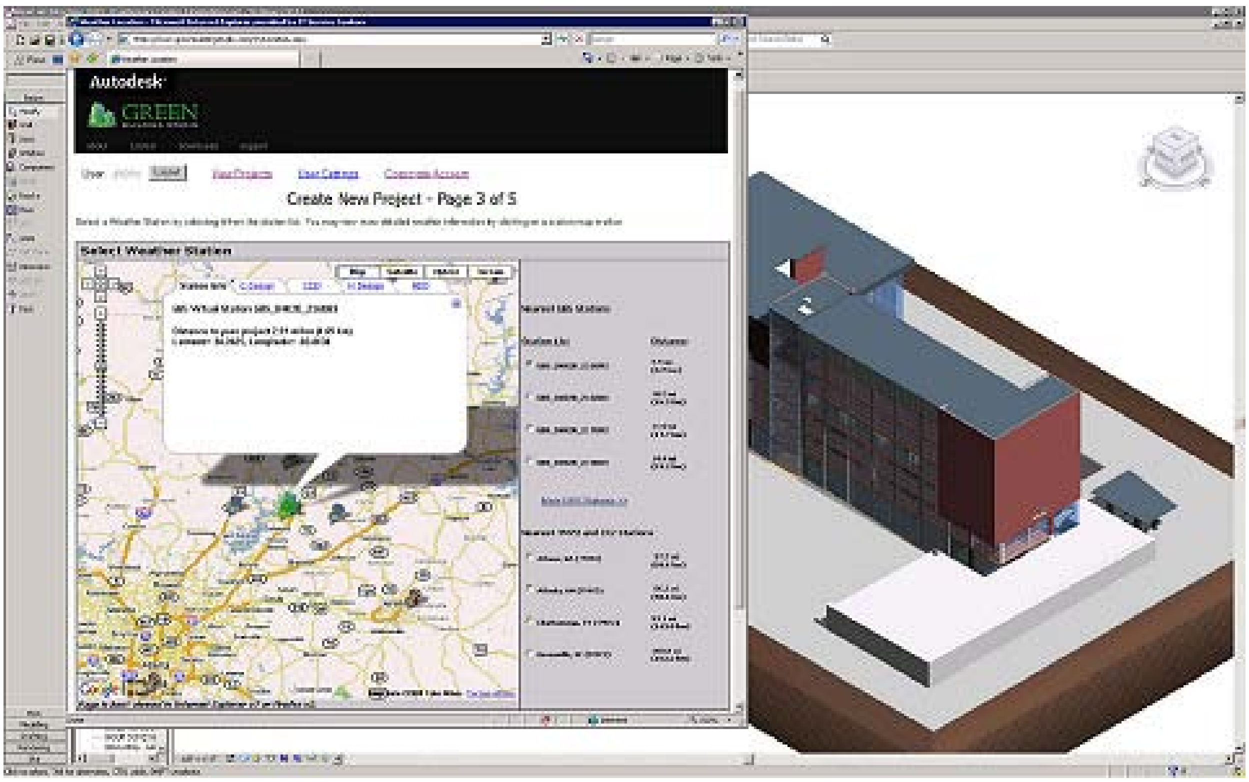


Figure 3-12. Set up project location in GBS. (Source: Rundell 2008).

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 the United States 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 a building's carbon emissions and the user is able to view the output in a web browser, including the estimated energy and cost summaries as well as the building's carbon neutral potential. Users can then explore design alternatives by updating the settings used by the service and rerunning the analysis, and/or by revising the building model itself in the Revit-based application and then rerunning the analysis.

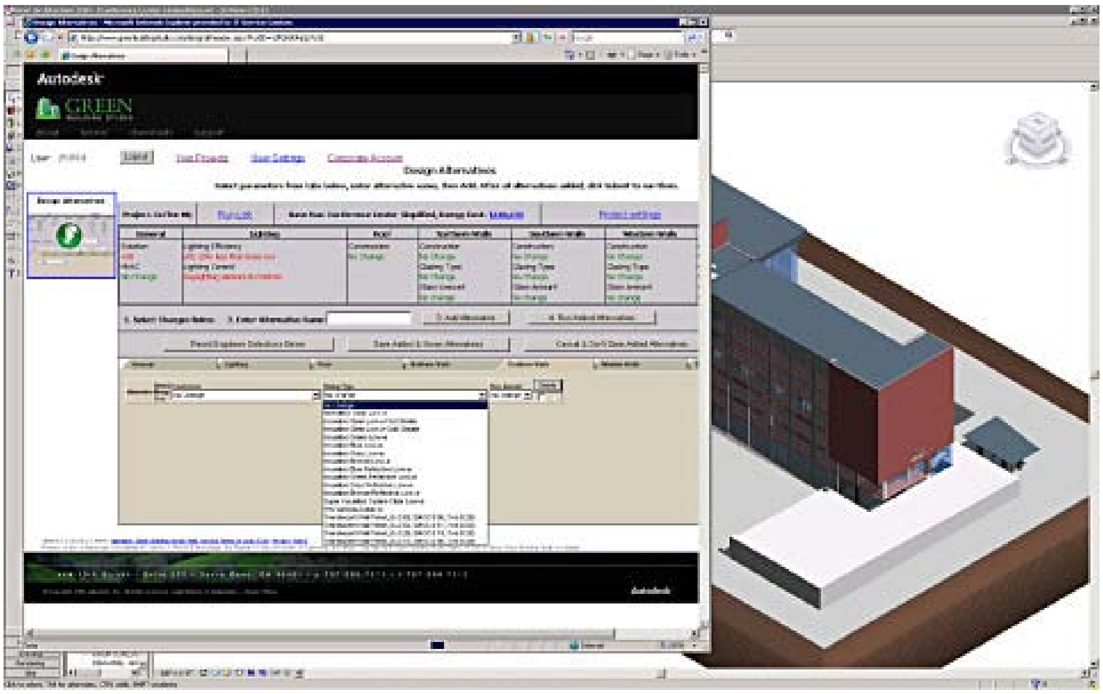


Figure 3-13. Design alternative configuration in GBS. (Source: Rundell 2008).

LEED Water Analysis Using GBS

Green Building Studio also summarizes the water usage (indoor and outdoor) and costs based on the project location, building occupancy type and fixture selection. LEED project teams will find the water calculation in GBS valuable since it is catered to address the requirements of the LEED Water Efficiency category (Figure 3-14). With a simple click, the project team could tell how many points the project could potentially achieve. Then with the computing table, designers can alter the fixture types by efficiency, and find the optimal strategy to achieve the desired LEED points (Figure 3-15).

For really ambitious project teams, GBS also suggests measures to achieve net-zero potable water usage through rainwater harvesting, graywater reclamation, and xeriscaping (using indigenous plants to eliminate supplemental landscaping irrigation). The associated cost savings of net-zero measures will also be estimated (Figure 3-16).

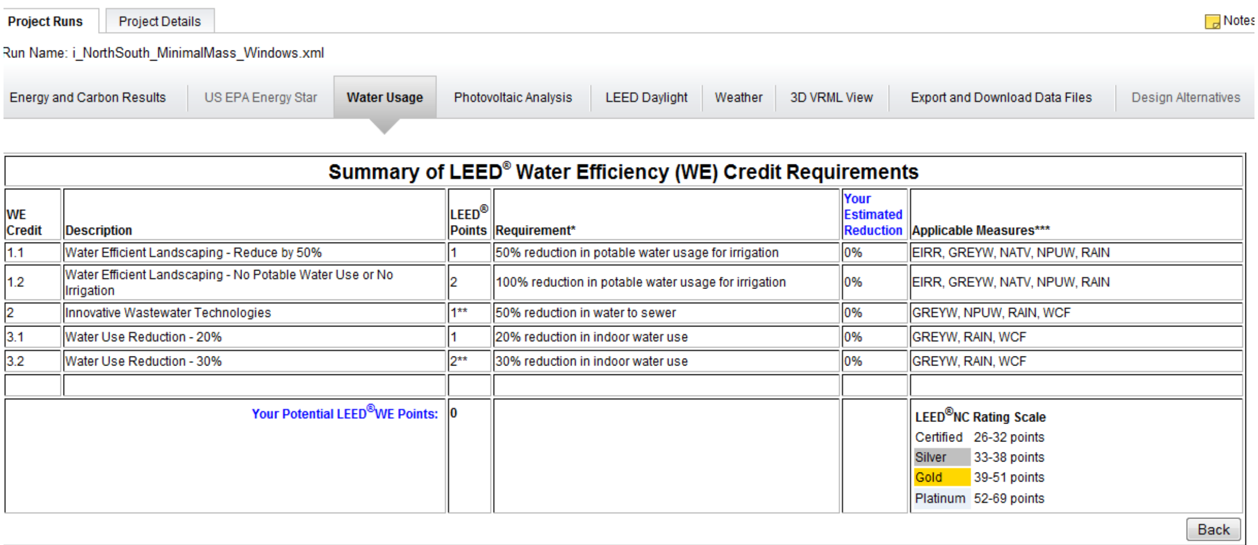


Figure 3-14. LEED water credit calculation in GBS.

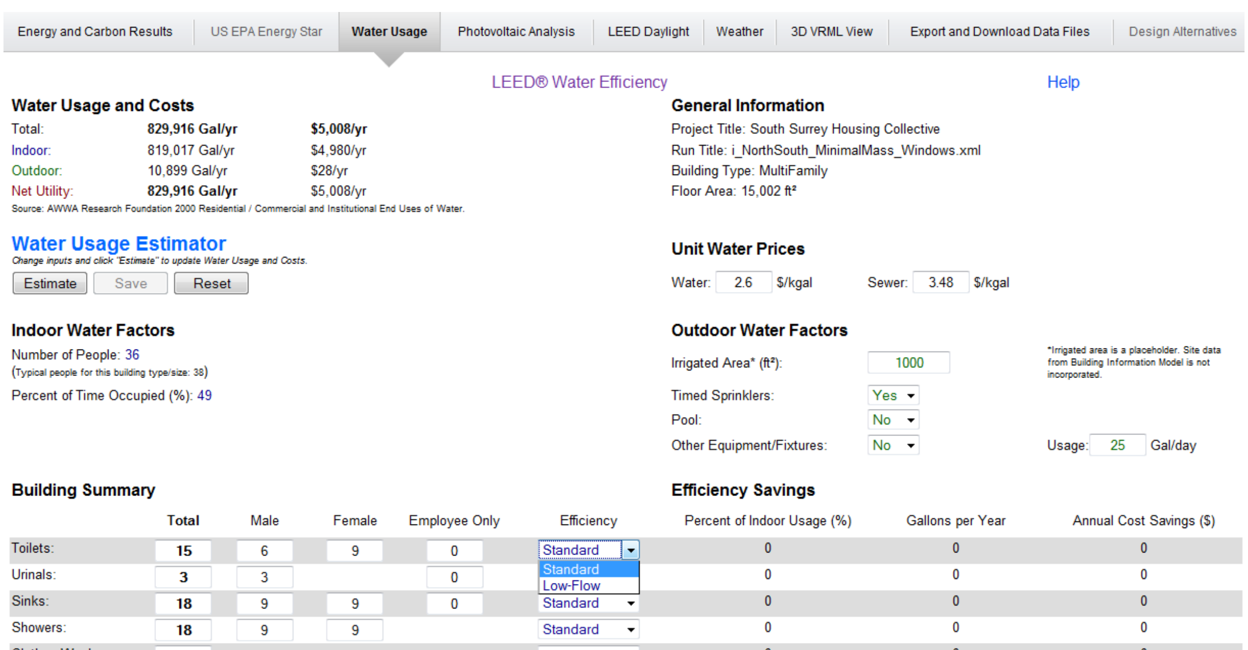


Figure 3-15. Configure plumbing fixture efficiency in GBS.

Net-Zero Measures				Net-Zero Savings		
		Annual Rainfall (in)*	Catchment Area (ft²)	Surface Type	Gallons per Year	Annual Cost Savings ($)
Rainwater Harvesting:	Yes	40.75261	7676	Gravel/Tar	155,991	406
Native Vegetation Landscaping:	Yes				3,707	10
Greywater Reclamation:	Yes				2,725	17
Site Potable Water Sources:	No	Yield:	0	Gal/day	0	0
*Source: National Climactic Data Center, #CLIM81.				Total Net-Zero Savings:	162,423	$432

Figure 3-16. Achieve net-zero potable water in landscaping.

LEED Daylighting and View Analysis

Daylighting and view is important to green building. Americans spend on average 90% of their time indoors. The well-being and productivity of occupants can be improved by providing views to the exterior and by providing daylighting (USGBC 2007). A well-designed daylit building is estimated to reduce lighting energy use by 50 to 80% (Public Technology Inc. 1996). Daylighting design involves a careful balance of heat gain and loss, glare control, visual quality and variation in daylight availability. Shading devices, lighting shelves, courtyards, atriums and window glazing are all strategies employed in daylighting design. Important consideration include the selected building's orientation, window size and spacing, glass selection, reflectance of interior finishes and locations of interior walls.

Both IES<VE> (Figure 3-17) and GBS (Figure 3-18) can conduct comprehensive daylighting and view simulation, with direct input of building orientation, geometry data, openings, shading device, glazing ratio, types and reflectance from the building information model. The process again is facilitated by the use of gbXML as the interpreter between the model information and the analysis engine. The results of these simulation are already made compatible with the LEED requirements, thus can be included by the project team in the submittals to GBCI for credit review.

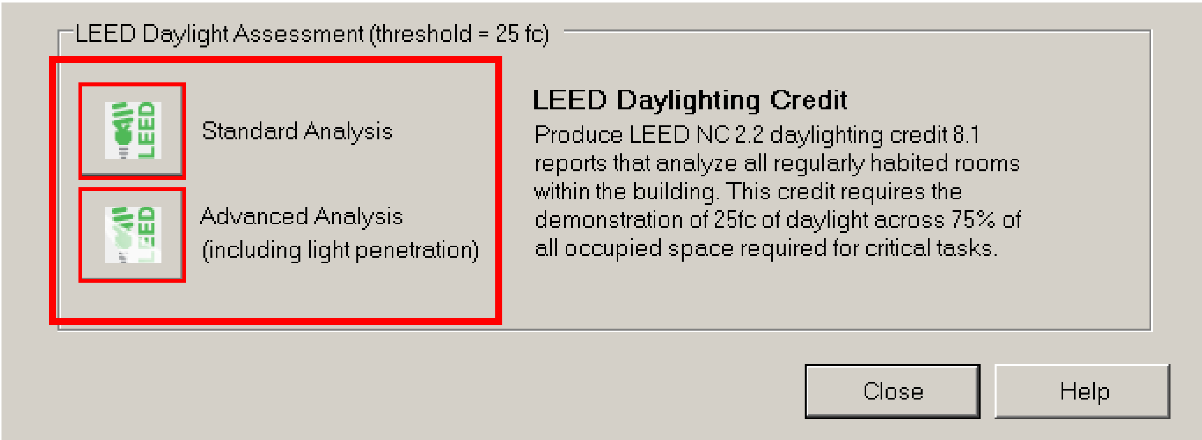


Figure 3-17. LEED daylighting assessment module in IES<VE>. (Source: Haynes 2008).

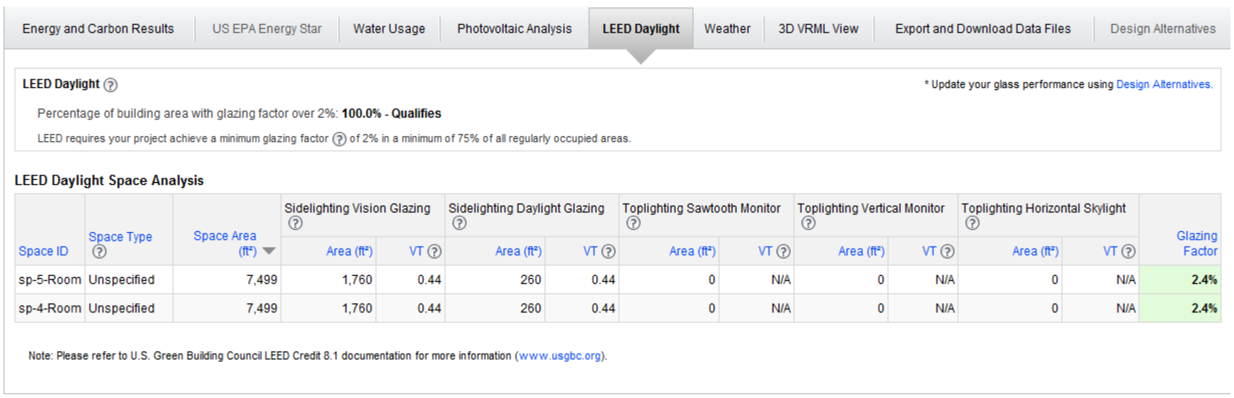


Figure 3-18. LEED daylighting analysis in GBS. (Source: GBS 2009).

BIM for Sustainability: Academic Research

In parallel with the technology advancement in the industry, academia has made progress in quite diverse areas with investigating the potential of BIM's implementation in building sustainability.

Laine and Karola (2007) identified that the main barrier preventing wider usage of dynamic energy analysis had been the large amount of work required to manually input data. They commented that by utilizing BIM as a data source for energy analysis, the data input would be more efficient and the existing data more reusable. They noted that only by using BIM, the verification of thermal performance could truly happen in different phases of the building process. They described a new concept and interoperable software environment for management of thermal performance during the whole building life cycle. Schlueter and Thesseling (2008) proposed a prototypical tool integrated into BIM software, enabling instantaneous energy and exergy calculations and the graphical visualization of the resulting performance indices, resulting in a higher flexibility of measures to optimize a building design.

Huang et al. (2008) critiqued the defects of current simulation tools in terms of lack of interoperable tools and the difficulty in assessing tacit expert knowledge across building disciplines. They proposed a new scalable lighting simulation tool developed with the objective of reducing the time and effort required to use lighting simulation tools in integrated concurrent design. The simulation tool was based on the automatic creation of lightweight specific Domain Object Models (DOM) suitable for use by lighting simulation. The seamless sharing and reuse of building information between the design tool (Revit), the energy tool (EnergyPlus via Green Building Studio) and the new lighting simulation was thus achieved.

Gillard et al. (2008) discussed and illustrated how the use of BIM could be an essential tool for the design and maintenance of buildings, which were to be refurbished following a sustainable methodology. It was based upon a case study that explored how a small design practice, using ArchiCAD 3D BIM interchangeably with Ecotect building performance analysis software, could thus compete with major design practices in providing a superior service to clients, by demonstrating that the regeneration of a group of existing buildings is both more cost effective and more sustainable than new build.

Integration Framework Development

The efforts to integrate building information modeling and sustainability in the AEC industry come into two major forms: "spontaneous integration" and "systematic integration". Previous paragraphs have been focusing on the spontaneous efforts that come directly from empirical evidence in the field and research on the specific technology application in a particular building system. However, it is critical to investigate the full potential of this integration by taking a holistic view for the following reasons:

- Spontaneous efforts tend to be fragmented and case dependent. The success may or may not be documented and archived. The knowledge often is kept to the project only and thus cannot be referenced by future projects. Besides, building projects vary from one to the other significantly; experience learned in one project may not be applicable to other projects at all. Thus the benefits of empirical experience are usually limited to demonstrating the possibility instead of suggesting standard practice that could be replicated by the industry; and
- Research on a particular building system is meaningful only to the extent that how much impact the system generates on the whole building. In contrast, a "whole building" approach provides the strategies to achieve a true high-performance building: one that is cost-effective over its entire life cycle, safe, secure, accessible, flexible, aesthetic, productive, and sustainable. Through a systematic analysis of these interdependencies, and leveraging whole building design strategies to achieve multiple benefits, a much more efficient and cost-effective building can be produced (WBDG 2010).

A holistic integration of BIM and sustainability will be at the framework level. The key elements of this integration framework include: interoperability facilitated by IFC and XML; the internalization of sustainability within BIM; and the use of a code checking approach to perform sustainability compliance analysis.

Interoperability

Information and exchange constitute the essence and key activities of BIM (Figure 3-19). Fragmentation of the AEC industry is compounded by the diverse BIM solution market. It is not unusual that stakeholders engaged in the same project use distinct software solutions, especially when their roles require unique features of specific application. It is unrealistic to mandate that a completely interoperable package of BIM solutions should be adopted across the project in that the project team is only a temporary collection of different stakeholders, starting when the project kicks off and ending at the moment when the project is accomplished. Transient partnership in the AEC industry to some extent eliminates the possibility to achieve a single-sourced, unilateral software solution for all companies in the industry. The direct impact of this heterogeneous environment for a building project is the loss of productivity. This is analogous to the project team members speaking different languages without an interpreter. Consequently, communication is severely handicapped, critical project information and data fail to be accurately disseminated.

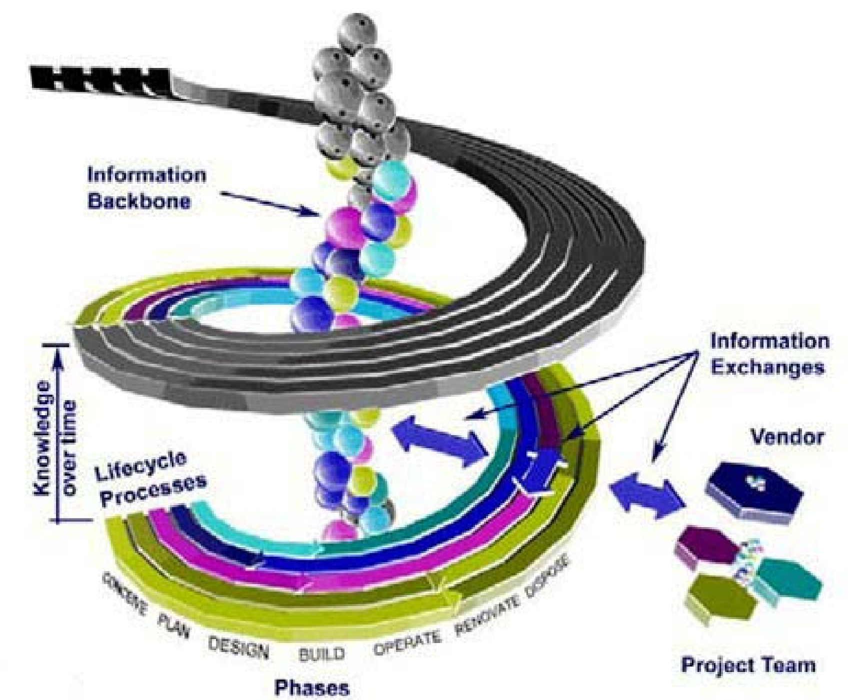


Figure 3-19. Facility lifecycle helix. (Source: NBIMS Committee 2007).

Interoperability responds to the need to share data between applications, allowing multiple types of experts and applications to contribute to the work at hand via a specially contemplated format. Major exchange formats for interoperability now are typically carried out using one of the following four main approaches (Eastman 2008):

- Direct, proprietary links between specific BIM tools;
- Proprietary file exchange formats, primarily dealing with geometry;
- Public product data model exchange formats (IFC and CIS/2); and
- XML-based exchange formats

IFC and CIS/2 are the only public and internationally recognized standards today. Due to the limitation of CIS/2 to steel fabrication, the IFC data model is likely to become the international standard for data exchange and integration of the building construction industries. On the other hand, XML allows definition of the structure (often called schema) and meaning of the data of interest. The different schemas support exchange of many types of data between applications and they are especially good in exchanging small amounts of business data between two applications set up for such purpose.

IFC and its support for sustainability

Industry Foundation Class (IFC) is an ISO standard (ISO/PAS 16739) for exchange of construction data. The development, maintenance, and use of IFC and IFC enabled products are part of the buildingSMART initiative of the International Alliance for Interoperability (IAI). The term “buildingSMART” 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 AEC software applications. The AEC industry is, by its nature, fragmented and distributed. It also encompasses a very large set of interoperability requirements. Many axes could be described along which those requirements occur and can alter, such as:

- Disciplines involved in AEC/FM processes;
- Life-cycle stages of AEC/FM projects; and
- Software application types used.

To satisfy all 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 diversified modules. Therefore the IFC Schema was set up:

- As a single integrated schema to enable cross discipline, life cycle and level of detail exchange; and

- Using a modular architecture to facilitate the specialization of discipline and life cycle specific modules within the integrated IFC Schema.

In IFC each object is traceable with its own “birth number”, the GUID (Global Unique ID). The vision behind the buildingSMART is to enable efficient information flow during the complete lifecycle of the building. IFC compliant building information models form part of the foundation to this vision (Kiviniemi et al. 2008).

In general, to be able to share information, three specifications must be in place (Bell and Bjørkhaug 2006):

- An exchange format defining HOW to share the information. IFC is such a specification;

- A reference library defining WHAT information we are sharing. The IFD Library (an implementation of ISO 12006-3) serves this purpose; and

- Information requirements defining WHICH information to share WHEN. The IDM/MVD approach forms that specification.

IFC was developed as an extensible framework model to provide broad general definitions of objects and data from which more detailed and task-specific models supporting particular workflow exchanges can be defined. It was designed to address all building information (implies the inclusion of building performance and sustainability information), over the whole building lifecycle, from feasibility and planning, through design (including analysis and simulation), construction, to occupancy and operation (Khemlani 2004). As of 2008, the current release of the IFC is Version 2x4 beta 3. Figure 3-20 shows the system architecture of IFC sub-schemas.

IFC is not the data per se but an exchange format that could facilitate data exchange between different software applications. In regard to sustainability, pertinent research is currently conducted by the European research group EUROPE INNOVA (http://www.europe-innova.eu/web/guest/home), with their noticeable STAND-INN series of reports on IFC support for sustainability integration in buildings.

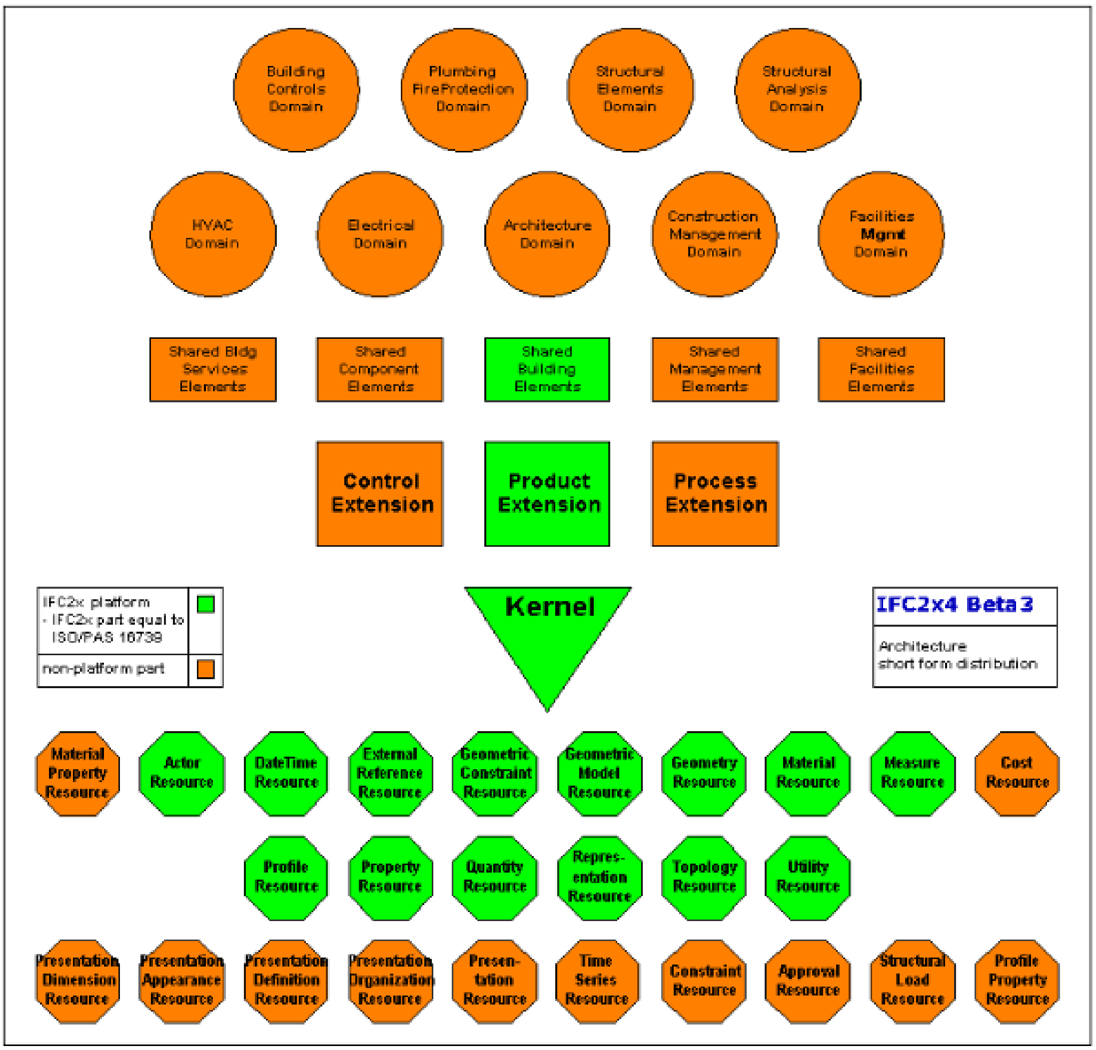
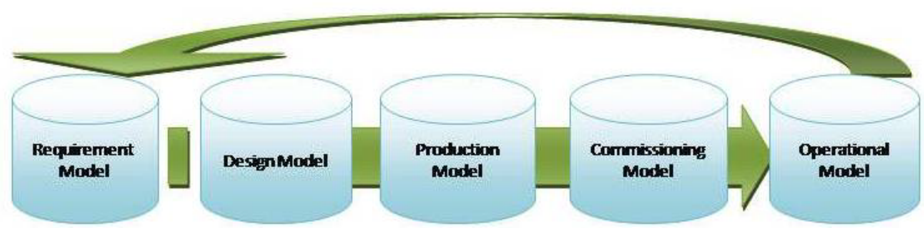


Figure 3-20. Architecture diagram of IFC 2x4 Beta 3. (Source: IAI 2009).

The STAND-INN (2007) report series covered a wide range of investigation on IFC support for sustainability, including Deliverable 13: IFC Support for Sustainability; Deliverable 15: IFC and IFD Feasibility for Innovative Sustainable Housing; and Deliverable 16: Guidance on IFC/IFD for Innovative Sustainable Housing. The impacts of the STAND-INN research were far-reaching. As for IFC/BIM and sustainability, the deliverables of this research are:

- Established a life cycle based sustainable construction roadmap using building information models (Figure 3-21); and
- Identified the IFC/BIM supported sustainability indicators/applications (Table 3-4).



	Required Sustainability	Designed Sustainability	Constructed Sustainability	Delivered Sustainability	Achieved Sustainability
Performance	Targeted performance in use	Designed technical solutions	Constructed building	Validated conformity	Performance in use
LCA	Estimated life cycle environmental, social and economical impacts	Estimated environmental impacts over the life span	Construction impacts, estimated impacts in use	Estimated environmental impacts in use	Environmental impacts in use
LCC	Estimated life cycle costs	Estimated life cycle costs	Construction costs, estimated operation costs	Estimated operation costs	Operation costs, demolition costs, value of building

Figure 3-21. IFC/BIM supported sustainable construction. (Source: Haagenrud 2007).

Table 3-4. IFC/BIM supported sustainability applications (Source: Haagenrud 2007)

Sustainability Applications	Support Level (increase by number of "√")
Life Cycle Assessment (LCA)	√
Environmental Product Declaration (EPD)	√
Life Cycle Costing (LCC)	√ √ √ √ √ √ √
Energy Performance Declaration	√ √ √ √ √ √ √ √ √ √
Environmental Impact	√ √ √ √ √ √ √
Adaptability to change in use	√ √ √
Reusability/Recycling	√
Service life planning	√
Social Impact	√ √ √
Energy efficiency	√ √ √

XML and its support for sustainability

Extensible Markup Language (XML) has become very popular for information exchange between Web applications, e.g. to support e-commerce 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. The schema determines what data and how the data will be stored and presented. Current XML schemas in AEC industry include but are not limited to:

- The aecXML is an XML-based language used to represent information in the Architecture, Engineering and Construction (AEC) industry. This information may be resources such as projects, documents, materials, parts, organizations, professionals, or activities such as proposals, design, estimating, scheduling and construction. It is intended to be used as an XML namespace and to facilitate information exchange of AEC data on the Internet (www.aecxml.org);

- The agcXML project, inaugurated and funded by The Associated General Contractors of America (AGC), resulted in a set of XML schemas for the transactional data that is now commonly exchanged in paper documents such as owner/contractor agreements, schedules of values, requests for information (RFIs), requests for proposals (RFPs), architect/engineer supplemental instructions, change orders, change directives, submittals, applications for payment, and addenda, to name a few. The agcXML Project is being executed as part of the aecXML domain framework under the auspices of buildingSMART alliance (www.agcxml.org);

- The gbXML (Green Building XML) has been discussed in previous paragraphs in the energy simulation part. The gbXML open schema 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. In addition, with the development of integration modules inside major engineering analysis tools, gbXML has become the defacto industry standard schema. Its use dramatically streamlines the transfer of building information to and from engineering analysis tools, eliminating the need for time consuming plan take-offs. This removes a significant cost barrier to designing resource efficient buildings and specifying associated equipment (www.gbxml.org); and

- 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 specifics of 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 advantages of using XML as the information exchange format were summarized by Liebich (2002) as:

- XML was commonly used and relevant XML knowledge was widely available in companies and organizations;
- Variety of development tools were cheaply available; and
- XML was easy to integrate with browser and other standard software.

Internalize Sustainability within BIM

Perceiving the broad pursuit of green building in the industry and the popularity of BIM technology, some scholars have been working on strategies to internalize the sustainability within BIM. This entailed the creation of a customized sustainable design criteria embedded in the existing BIM authoring tools. Ideally, the designers would have access to prescribed sustainability requirements from the inception of the building design. An immediate practical set of sustainability criteria is easily found in a green building rating system.

Biswas et al. (2008) briefly illustrated how a sustainable building rating system could be adopted into a building information model to offer designers an environment to work with an enhanced integrated awareness of different sustainability factors. A general framework of sustainable measures was proposed to encompass the categories and subcategories of commonly used rating systems. A prototype sustainable building information model (SBIM) application was proposed to aid designers in keeping in mind the different design aspects that they needed from the early design phases.

Barnes and Castro-Lacouture (2009) described a BIM-enabled integrated optimization tool for LEED decisions. The optimization tool would assist project stakeholders in the selection of material, equipment and systems at every stage of the construction project life cycle, considering the best value with regard to the applicable green building rating system score, e.g. the LEED system. Using BIM in this approach, Barnes and Castro-Lacouture argued, would allow owners, designers and contractors to choose the item on the spot from a 4-D representation. Thus the decisions could be made in a timely fashion and with effective communication to cut down on additional costs that were inevitable in large-scale construction projects.

Code Checking: Sustainability Compliance

The idea of using BIM technology to check projects' compliance with building codes was first adopted in Singapore. The Construction and Real Estate Network (CORENET) initiative was launched in 1995 and its aim was "to reengineer and streamline the fragmented work process in the construction industry, so as to achieve quantum improvements in turnaround time, quality and productivity". To drive the seamless exchange, management, comprehension and integration of project information or interoperability across diverse platforms, the adoption of building information modeling was identified as a critical cornerstone (Teo and Cheng 2005).

The Building and Construction Authority of Singapore approved the implementation of the CORENET e-Plan Check System in 2004 (Figure 3-22). As illustrated, the three kernel modules in automatic code checking included: the e-Plan Check System, the Rules Schema (computer parsed building codes) and the IFC building information model (created by a BIM authoring tool). With this e-Plan Check System, building professionals (such as registered architects and professional engineers) could prepare their design using object-oriented BIM tools and then upload the BIM into e-Plan Check System for automatic on-line or batch processing. When the automatic checking process was completed, the system would generate a downloadable report to highlight the areas of non-compliance.

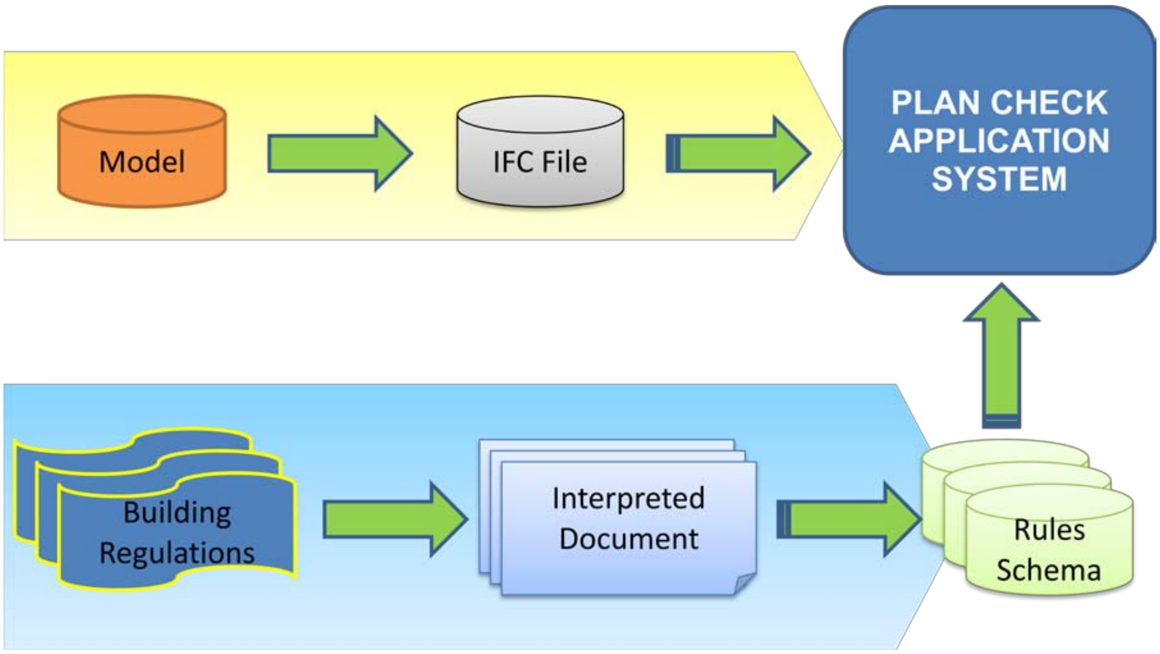


Figure 3-22. CORENET e-Plan Check System. (Source: Teo and Cheng 2005).

The conventional code checking and approval process using the manual approach was laborious and inefficient. With the e-Plan Check System, the checking process was significantly speeded up. With careful rule schema design, the ambiguities and subjectivity were also reduced in the building code interpretation and regulatory compliances.

New trends in the code checking research now include the engagement of construction safety and building sustainability. With a special interpreter, safety regulations such as the Occupational Safety and Health Administration (OSHA) standard in the U.S. could be written in the computer-readable format similar to the new

Rules Schema module in the e-Plan Check System. The same logic may apply to the sustainability except for the fact that sustainability or green building practice has not yet been written into building codes in any country around the world. However, the possibility is open, and some voluntary based initiatives have been working on the piloting efforts to realize quasi code-checking system for buildings' compliance with sustainability. The International Code Council (ICC) and their SMARTCodes project is a noteworthy example.

By collaborating with leading model checking software companies such as Solibri and AEC3, ICC set out to automate code compliance checking in the AEC industry. The SMARTCodes project is critical since it defines the machine- interpretable Rules Schema that contains the business rules to be checked against in the code checking process. Currently the most comprehensive SMARTCodes is the International Energy Conservation Codes (IECC). Meanwhile, the International Green Construction Code (IGCC) was published in March 2010 (ICC 2010). IGCC is conceived as a model code focused on new and existing commercial buildings addressing green building design and performance. The IGCC's unique drafting approach links the International Codes to a public process bringing together diverse areas of expertise to create the first integrated, regulatory framework for green commercial buildings. The code-checking approach to integrate sustainability into BIM is unique and may bring fundamental changes to current practice.

CHAPTER 4
METHODOLOGY

Overview

This chapter presents the methodology of this research. A phase-by-phase roadmap is implemented in this research:

1) Starting with a proof-of-concept survey, this research firstly looks into the actual needs, gaps and expectations in the industry regarding why and how applicable the integration of BIM and LEED rating system and certification is.

2) A generic integration framework is established to create the theoretic foundation for the BIM – LEED application model. Then a gap analysis is performed to find out what desirable functionalities are missing in current BIM solutions, especially in the Revit suite and supplemental software applications.

3) The BIM – LEED application model (or Revit – LEED application model in this particular software environment) consists of two modules: the LEED-oriented design assistance module and the LEED certification management module.

4) To verify the application model, a use case of the LEED Materials and Resources category is created. Figure 4-1 illustrates the logic of the research workflow.

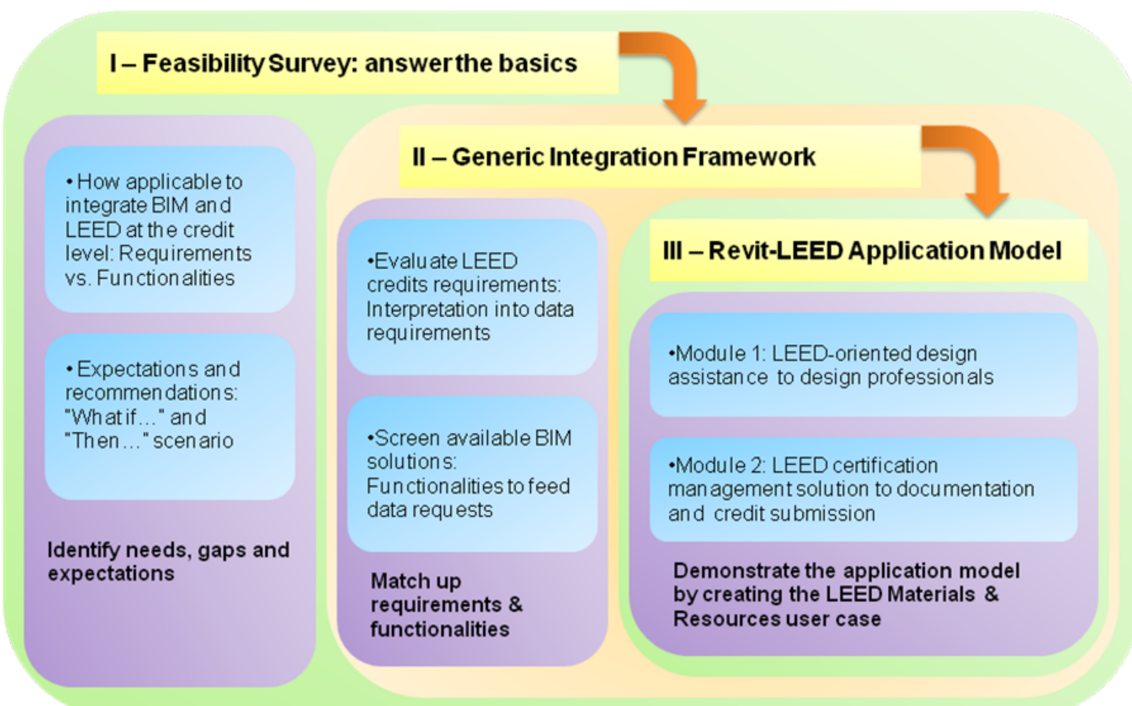


Figure 4-1. Research workflow.

Feasibility Survey

It is believed that the following pair of questions is critical to developing the integration framework:

- What does the LEED rating system and certification require?
- What solution can BIM provide?

Put another way, the first step to the generic integration framework should provide the answer to the following question: How do we match up the functionalities of BIM with the LEED certification requirements? The integration process has been handicapped due to the fact that so far no consensus has been reached as to how applicable and to what extent this integration can be. The survey was thus conducted to collect AEC professionals' opinions about how feasible it is in technology and operation terms to integrate BIM and LEED when breaking LEED down to the credit level along with the project delivery process. This survey also aims to find out what expectations and recommendations professionals have on this integration to make it more than a concept, a functioning mechanism. The results of this survey can then be used as a guideline for more in-depth development of the integration model.

The feasibility survey is designed for professionals in the AEC industry with different levels of involvement in BIM and LEED. It includes two major parts and a supplemental comment part. PART 1 asks four general demographic questions of the participants, and assesses their knowledge about BIM and LEED. Section 1 of PART 2 lists ten statements soliciting the participants' perception of the current BIM software tools in regard to their impacts on the LEED certification process in terms of cost, time, documentation, productivity and other typical issues in the project delivery. Section 2 of PART 2 addresses the structure of the LEED-NC 2009 rating system to investigate participants' opinions about the applicability of BIM – LEED integration at a credit-by-credit level. A complete survey questionnaire is attached in Appendix A.

Generic Integration Framework

The generic integration framework is established on the match-up of the LEED credit requirements and the functionalities available from current BIM solutions, for the purposes of this research, the Autodesk Revit software suite and supplemental software application from Autodesk. Two major tasks in establishing the framework include:

- **Evaluating LEED credits requirements:** Credits in the LEED rating system are organized in a consistent manner. Generally speaking, every credit has an accompanying explanation describing what issue that credit is trying to address; and the requirements elaborate the details that the project team should follow to be eligible for the applying for the corresponding LEED points. Credit requirements are descriptive and spell out the qualitative information that the project team should provide. More likely, the requirements specify the quantitative threshold of certain metrics that request for data. Since a major goal of the LEED rating system is to benchmark the building performance, the comparison conducted between the green building and the conventional building is inevitable. In this case, the project team should carefully interpret these requirements into the required data, and collect such data during the design and construction process; and

- **Screening available functionalities of Revit and supplemental BIM solutions:** The functionality inventory of these software applications may or may not be sufficient to satisfy the LEED credits requirement. For those credits with immediate available functionalities, a mark-up will be performed to lock the relationship between the requirements and the functionality. For credits that have complex data requirements, some joint functionality across different software may resolve the problem. However, it is possible that no existing functionality can meet the requirements of certain credits. In this case, a gap is identified to be evaluated later for possible solution.

In addition to the contents of the LEED rating system, the certification process involves extra commitment to administrative issues. Since LEED is a point system, the number of points the project can possibly achieve will directly determine the certification outcome. Thus it becomes important for the project team to monitor the status of the points balance. Ideally, this is done right at the inception of the project planning stage.

With the owner's expectation clearly spelled out, the project team will be able to work with the owner to go through the LEED checklist and find a strategy for what level of certification to look at; 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. This strategy is often called the "LEED Strategy" and the process is known as the "Design Charette".

The proposed integration framework should take the administrative aspects into account to provide the project team control over the LEED point status along with the project delivery.

BIM – LEED Application Model

The BIM – LEED application model operates on top of the integration framework. Once the owner decides to pursue the LEED certification, this application model is triggered. With the work done in the integration framework part, the application model will immediately obtain the data requests from the requirements for each credit. All the credits whose requirements can be met with existing functionalities will go through the necessary internal operation in the BIM solution for direct data feedback, then proceed to the preparation of relevant documentation and submittal, and eventually be ready for submission to USGBC through LEED Online (Figure 4-2). For the credits without support of immediate functionalities, two approaches are proposed to tackle the identified gaps:

- External information from other incompatible applications may still contribute data through the intermediation of IFC and XML; and
- New functionalities may have to be developed through the Revit API provided by Autodesk.

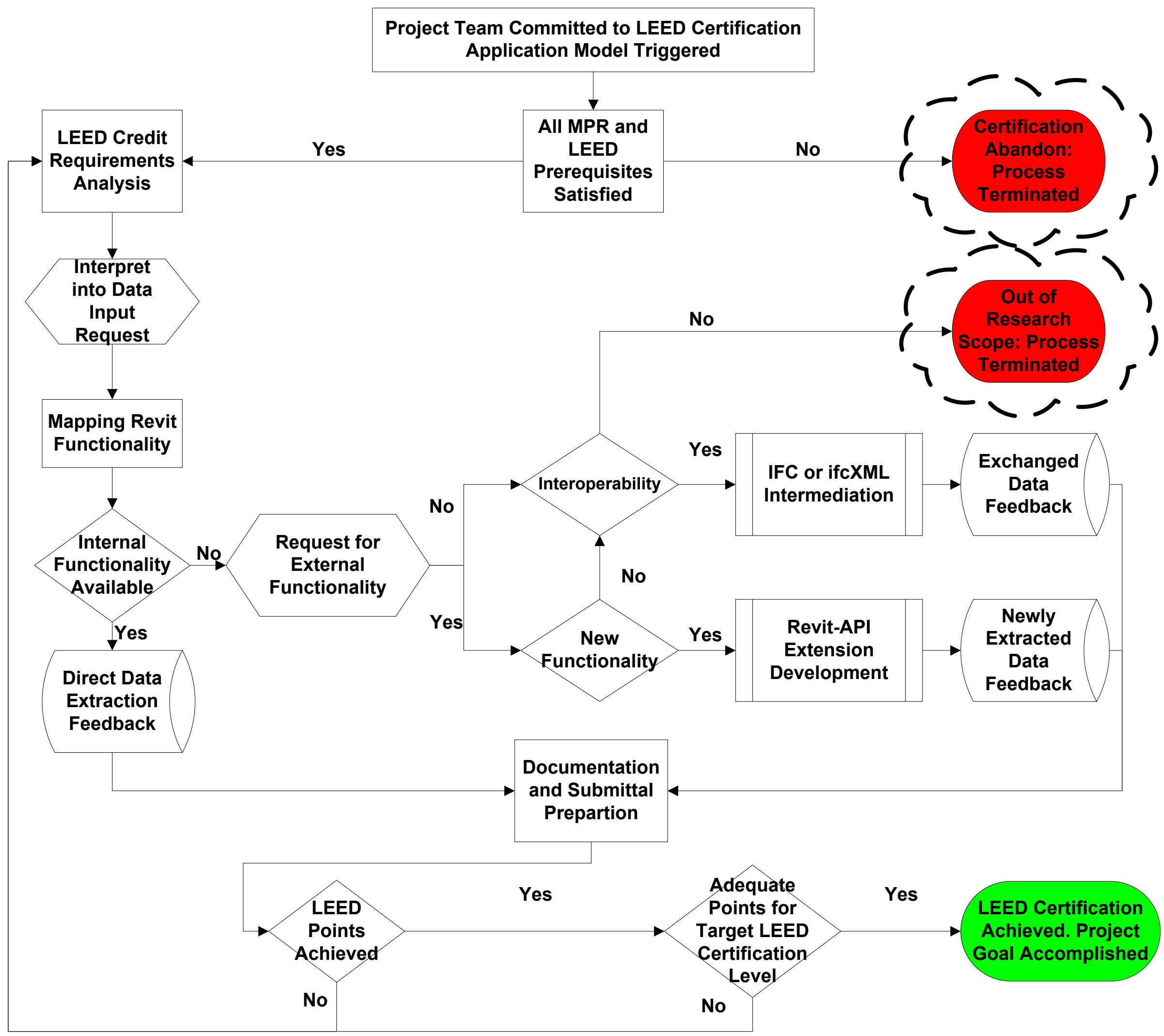


Figure 4-2. The logic flow of the BIM – LEED application model.

In regard to the contents of the BIM – LEED application model, it consists of two major modules:

- **The LEED-oriented design assistance module:** In order to extract data for the LEED certification purpose, the building information model in the first place should be created in a LEED-oriented manner. It is not unusual that the architects and engineers in a project are new to the LEED rating system. Even for accredited LEED professionals, the contents and details of the rating system are still overwhelming. To accommodate these subtleties, the application model provides designers real-time assistance in LEED information to ensure that the outcome building information model will cater to the certification needs.

- **The LEED certification management module:** The need to provide the project team especially the contractors a more efficient documentation management system is recognized. As previously discussed, documentation quality is the key to the success of the certification. A web-based certification management application built on the Apache/MySQL/PHP is then proposed to streamline the documentation generation, management and submission during the LEED project delivery. This module acts like a LEED-specific project management system with emphasis on information and documentation.

LEED Materials and Resources Use Case

The LEED Materials & Resources use case is created to verify the integration framework and preliminarily validate the BIM – LEED application model. All credits (including prerequisites) in the Materials and Resources category will be analyzed and interpreted into data requests. The functionalities will be mapped against these requests and gaps will also be identified.

The use case simulates the real LEED project delivery process. By implementing the application model step by step, the requirements to achieve the MR credits are fulfilled, the documentation to show such compliance and the submittals sent to GBCI for review are generated. Sample plug-ins are programmed into Revit to provide design assistance, and a prototype of the web-based LEED certification management application is developed.

CHAPTER 5
RESULTS AND DISCUSSIONS

Results: Feasibility Survey

The survey was deployed using the Zoomerang© web-based survey tool (http://www.zoomerang.com). The survey was active from June 30th, 2009 to August 1st, 2009 posted at LinkedIn (http://www.linkedin.com, a business-oriented social networking website) to professional groups including BIM Architecture, BIM Expert, BIM and the AEC Profession, BuildingSMART, Club Revit, Collaborative BIM Advocates, Green Revit API, Group for Building Information Modeling and Revit Users. These professionals represented a large number of active stakeholders in the BIM arena who routinely used the web as a means for information exchange and knowledge sharing. They had experience and felt comfortable with web-based research activities. Similar surveys have previously been conducted in LinkedIn among these same groups. A total of 190 people accessed the survey, 64 finished it partially and 35 (18% response rate) completed the questionnaire (some might have missed 1 or 2 questions). The results of the survey were then imported into a statistical software package (SPSS 17) for analysis.

Part 1: General Information

The participants in this study had the following backgrounds. Architects/Engineers constituted the greatest portion (20 out of 35), followed by general contractors (7 out of 35), owners (3 out of 35) and no (0) subcontractors responded (See Figure 5-1). The "Other" category (5 out of 35) included majorly consulting companies and BIM software vendors. The absence of subcontractors might be as meaningful as the dominance of the Architects/Engineers in the respondent group. Historically A/E companies are more resilient to technology transition due to their direct involvement in such transition, and often times they are the market drivers. Conversely, subcontractors are at a lower tier of the industry supply chain, and they are quite passive and tend to lag in adoption of innovative technologies. Lack of budget or fear of risks in using new technologies might also account for their reluctance to commit to BIM.

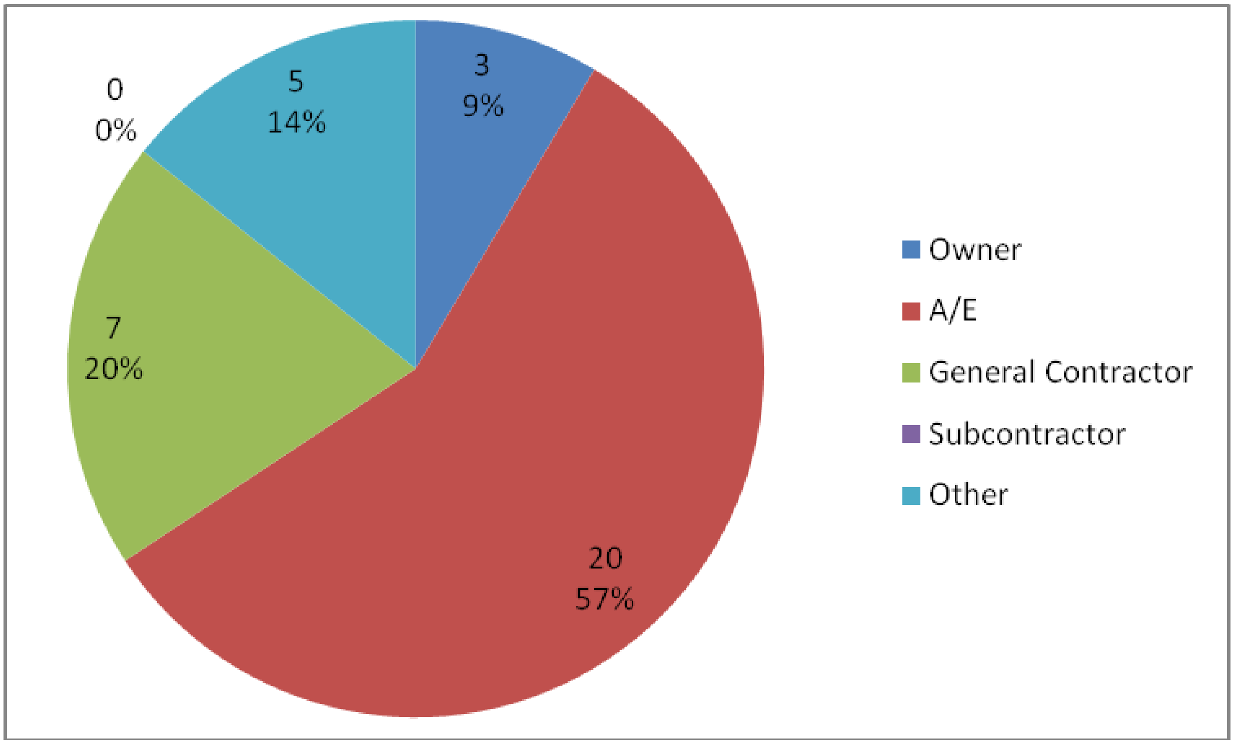


Figure 5-1. Company's role in a construction project.

Based on the definition of BIM from the NBIMS Committee (2007), 14 (40%) of the participants declared that they had previously participated in projects fully adopting BIM, while another 14 (40%) indicated that they had worked on projects that partially used BIM (see Figure 5-2). Only 2 (5.7%) admitted they had limited knowledge about BIM and knew the concepts only. The high BIM adoption rate by architects and engineers could be explained again in relation to the fact that architects and engineers were dominant in this survey, and they are earlier adopters of BIM according to McGraw Hill Construction (2008).

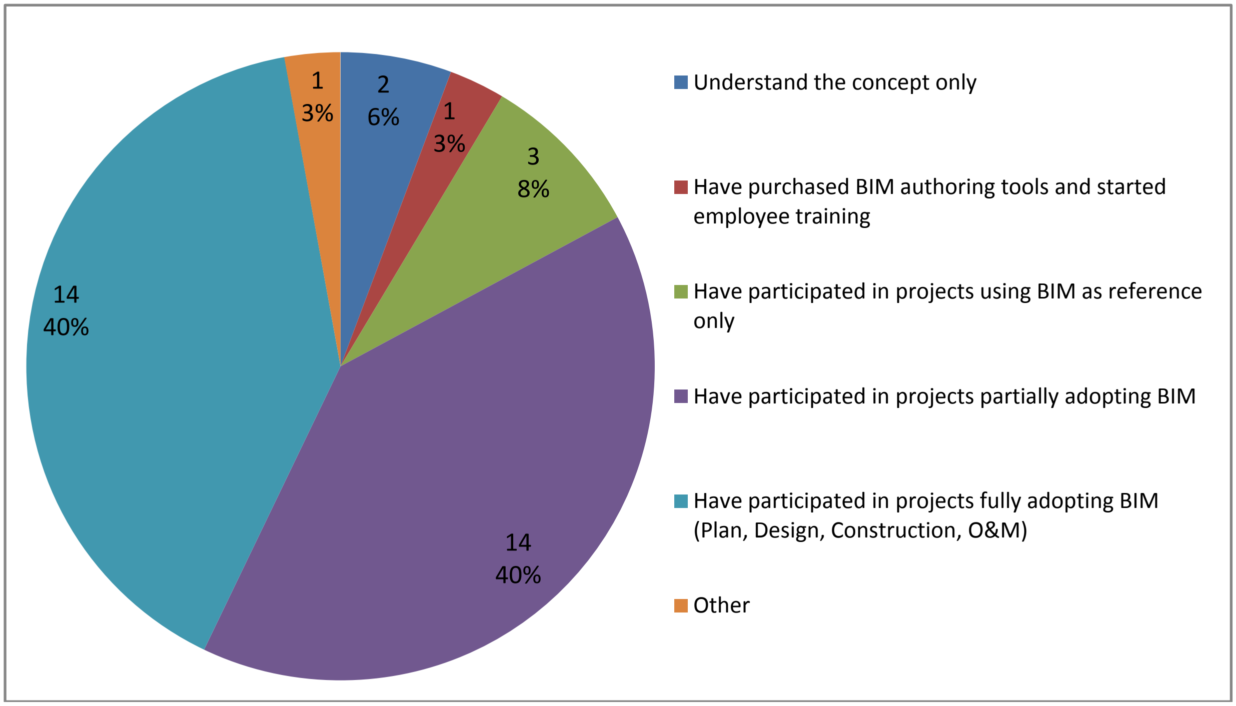


Figure 5-2. Company's experience with BIM.

There are various software applications of BIM in today's market. Despite the advantages and disadvantages of each of these varied applications, the Autodesk Revit software suite (including Revit Architecture, Structure and MEP) is arguably the most popular BIM software tools in the United States. The 74.3% usage rate of Revit in this study corresponded to the findings of the McGraw Hill's SmartMarket Report in 2008, which reported a 67% Revit adoption rate. Bentley System, ArchiCAD and Vico also had a certain market share (Figure 5-3). In the "Other" category, participants also indicated use of tools such as DProfiler, Digital Project, Onuma Planning System, Navisworks to name a few. The fact that lots of companies used more than one software application created concerns about interoperability issues due to the information exchange demands among software packages. As for LEED, chances are that not a single application can adequately tackle the complexity and magnitude of the issues encountered in the project delivery. Thus, it is inevitable to deal with the problems created by the use of different software applications. The prevalence of Revit has had an impact on the market since most peripheral software providers have preferred to develop plug-ins and add-ons compatible with the Revit platform, which will eventually contribute to the centralization of BIM solutions.

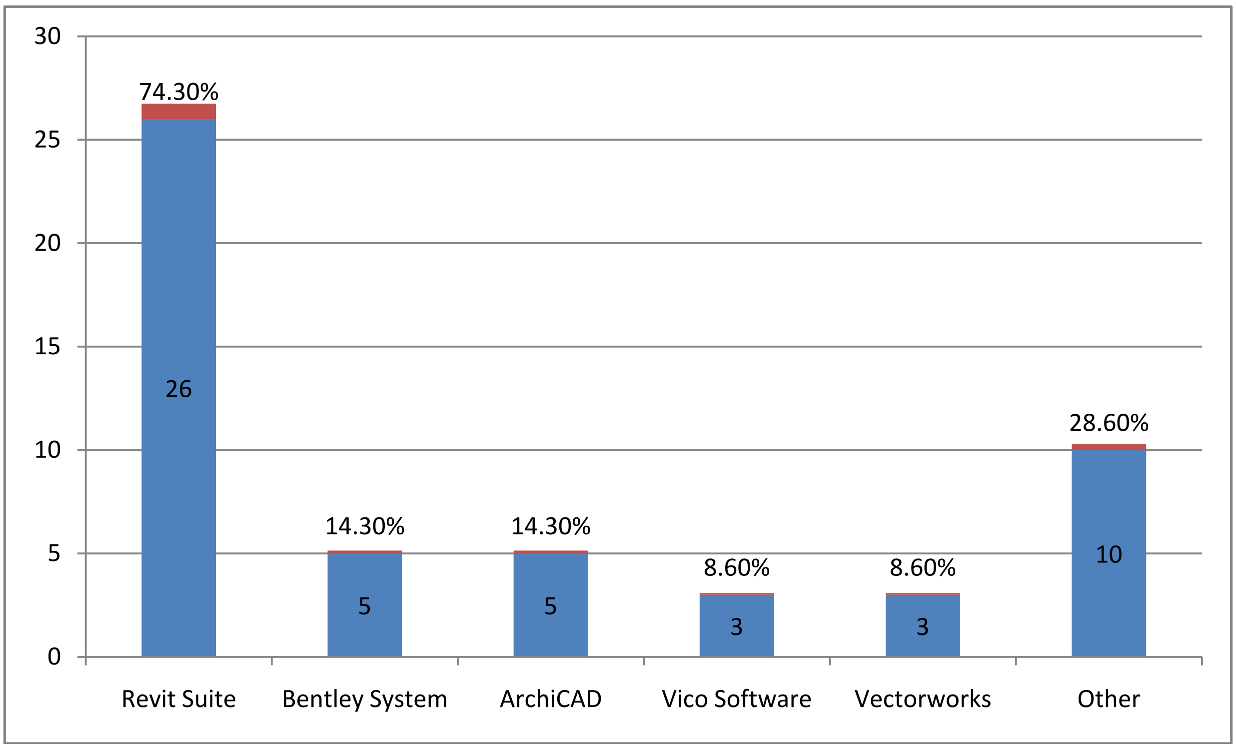


Figure 5-3. BIM authoring tools used by the respondents (select all that apply). For questions with multiple answers, the percentage is calculated by dividing the frequency by the total number of completed questionnaires (35).

When asked about their experience with the LEED rating system, as many as 26 out of 35 (74.3%) respondents indicated that they had previously worked on projects that successfully achieved the LEED-NC certification. A few of them (5 out 35, 14.3%) indicated that they had limited knowledge about LEED (See Figure 5-4). It seems from the survey results that the green building market has become quite mature in the United

Sates. The AEC professionals who had substantial understanding of the LEED rating system and who were practicing BIM, tended to be more inclined to leverage LEED project delivery with BIM.

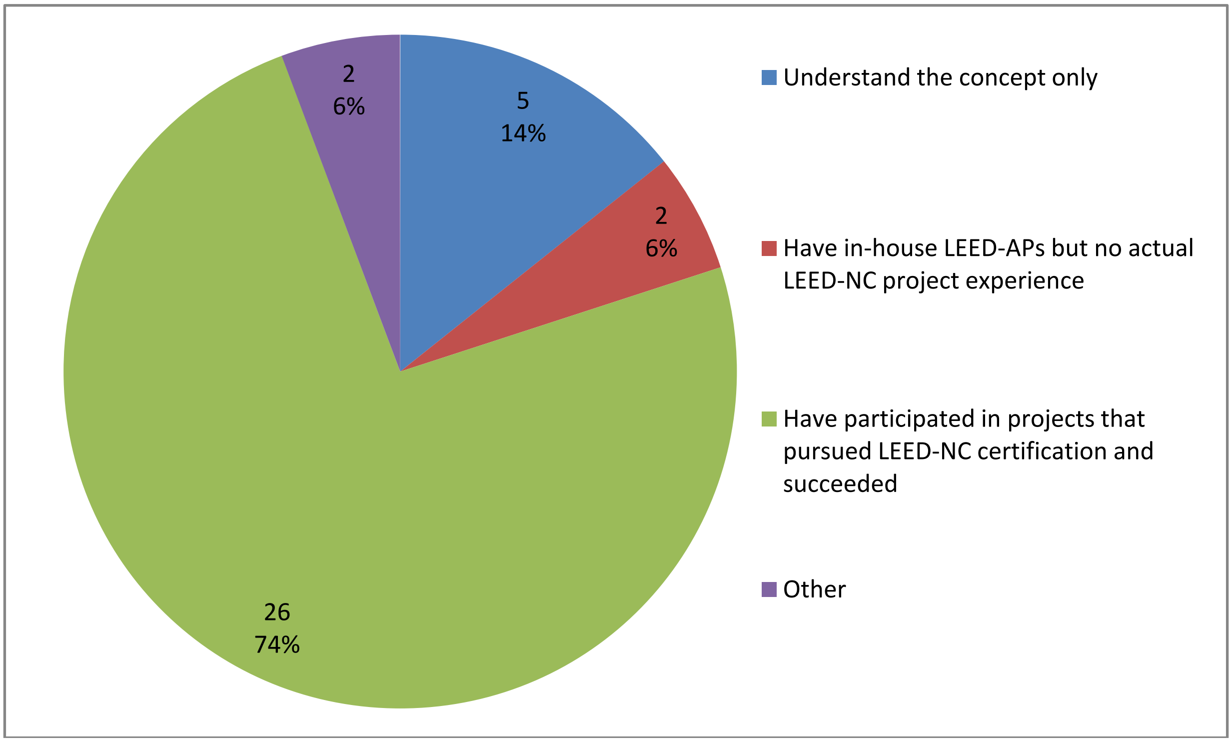


Figure 5-4. Respondents' company's experience with LEED-NC (all LEED-NC versions may apply). Considering that most completed or ongoing LEED-NC projects are prior to LEED-NC 2009, it is reasonable to include all versions here.

Part 2 – Section 1: Perception on Status Quo

Assumptions on how BIM would help sustainability and LEED certification vary from case to case. Lots of promises have been made without adequate justification. Essentially, it is not yet clear where the AEC industry is currently at in terms of realizing these promises. Lots of companies have been exposed to state-of-art BIM practice from case studies (e.g. Krygiel and Nies 2008) and marketing brochures distributed by software companies. But they do not have access to solid data that they can review and learn from so as to replicate the success in their own business operations.

Consequently, a benchmark of the status quo in BIM integration with sustainability and LEED becomes valuable to help companies pinpoint their positions in a competitive market. Section 1 of PART 2 in the survey used ten questions to solicit the perception of current implementation of BIM in LEED certification (majorly in the LEED-NC v2.2 certification). Each question was assessed using a 7-point Likert scale representing seven levels of perceptions ranging in value from “1” for “strongly disagree” with an increment of 1 to “7” for “strongly agree” (see Appendix A). It should also be noted that not all 35 participants completed all questions in this section, so the value of “N” was given in Figures 5-5 to 5-14 to indicate the number of valid answers that were actually attained.

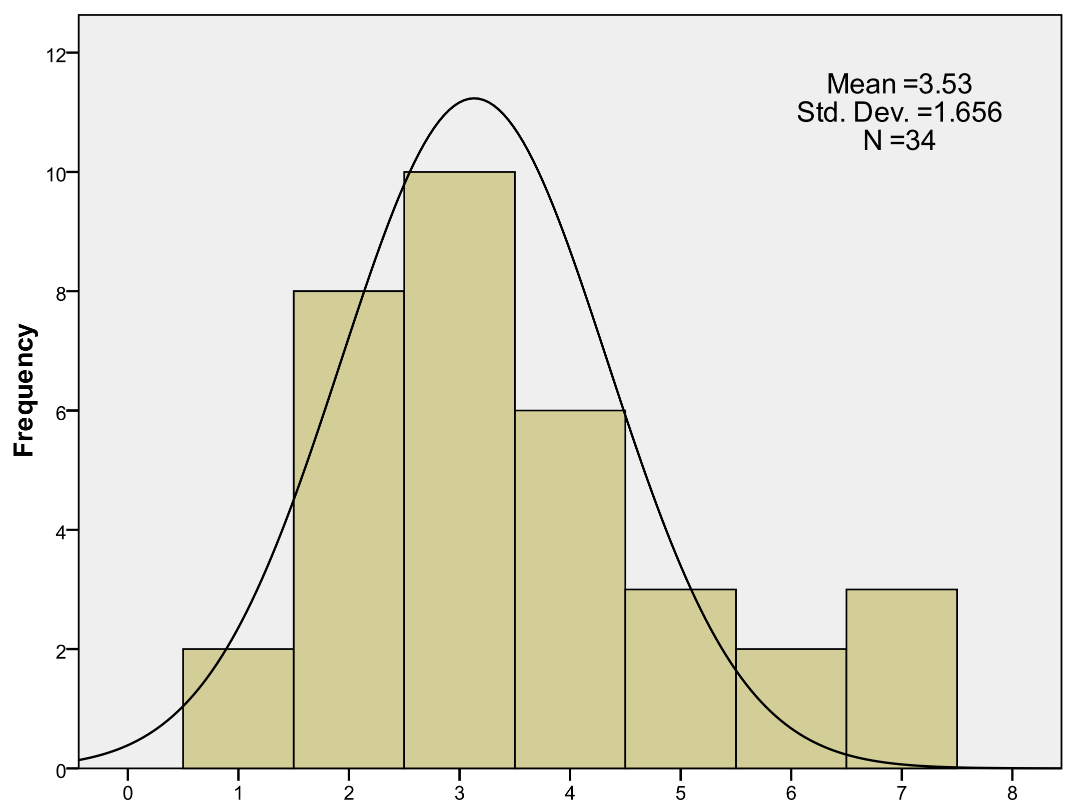


Figure 5-5. Current BIM solutions are adequate for LEED-NC v2.2 project delivery.

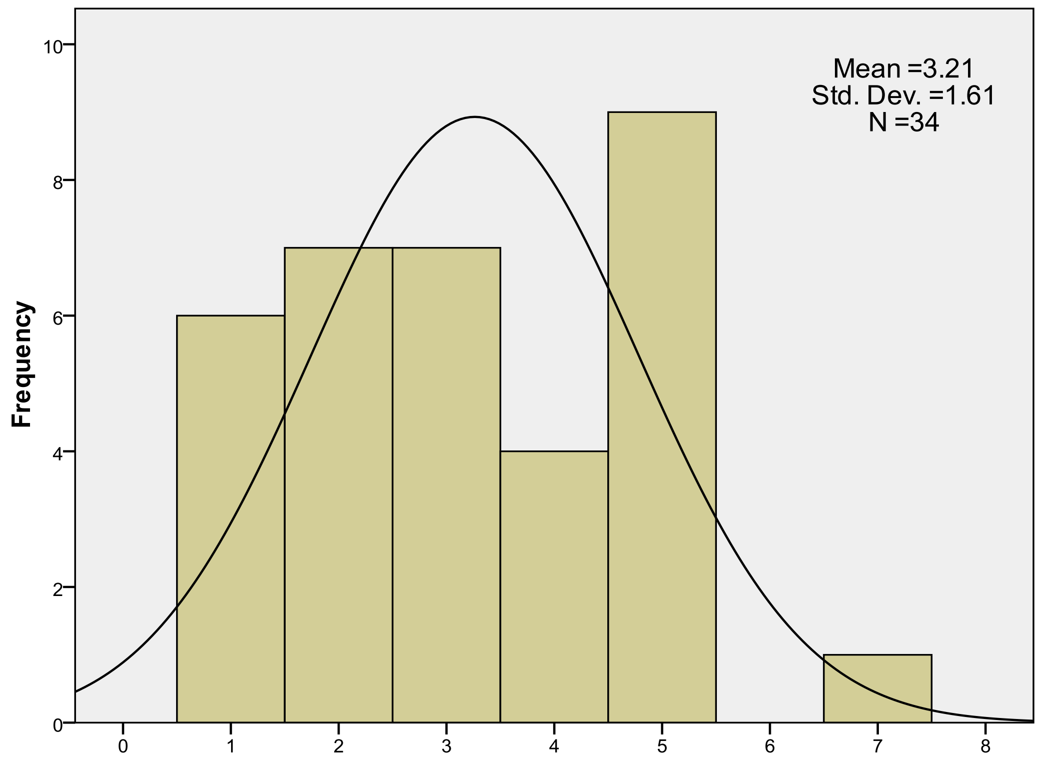


Figure 5-6. Full integration of BIM in LEED-NC v2.2 project delivery is realized.

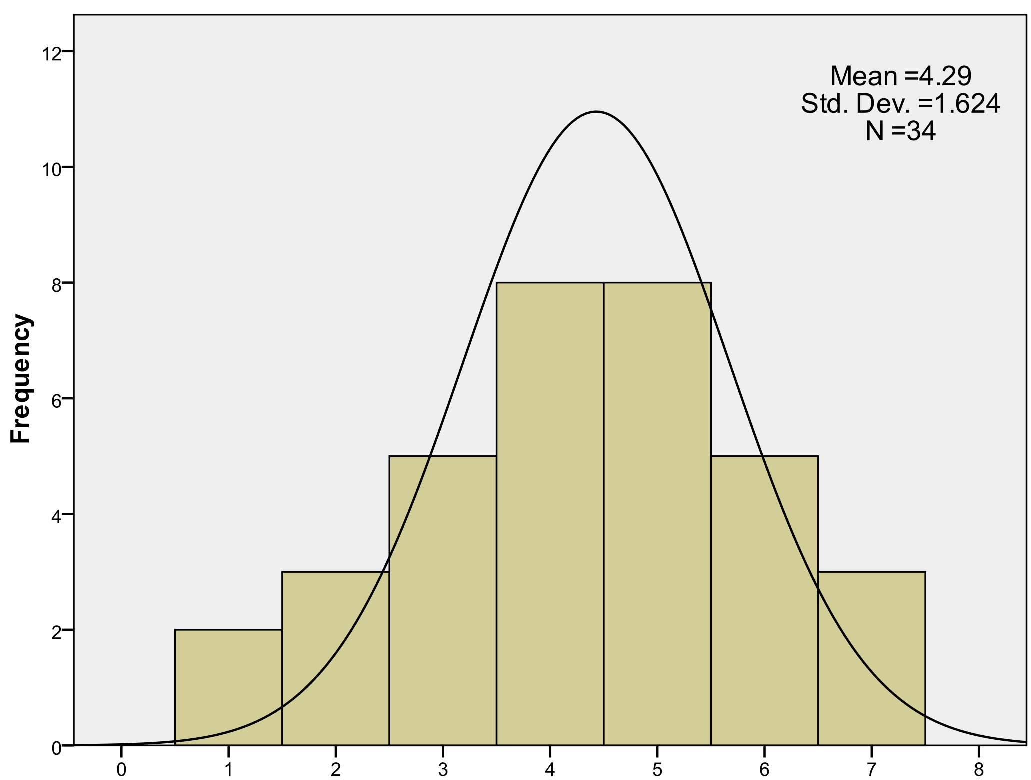


Figure 5-7. BIM is effective in the preconstruction stage of LEED-NC v2.2 projects.

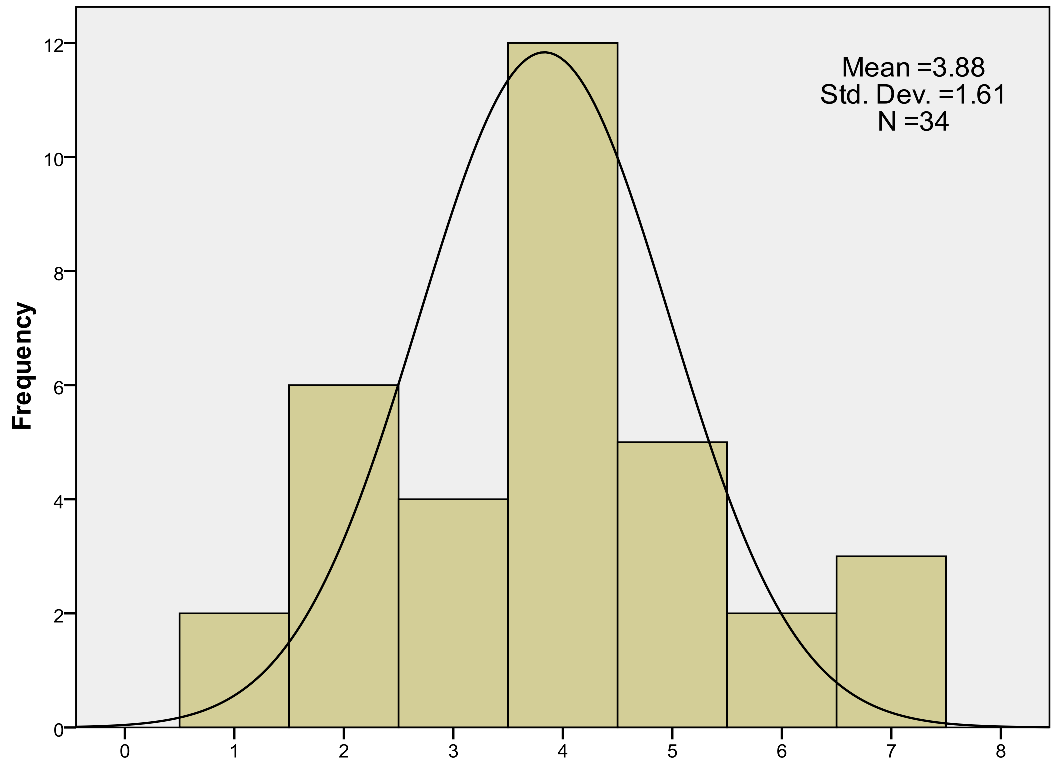


Figure 5-8. BIM is effective in the construction stage of LEED-NC v2.2 projects.

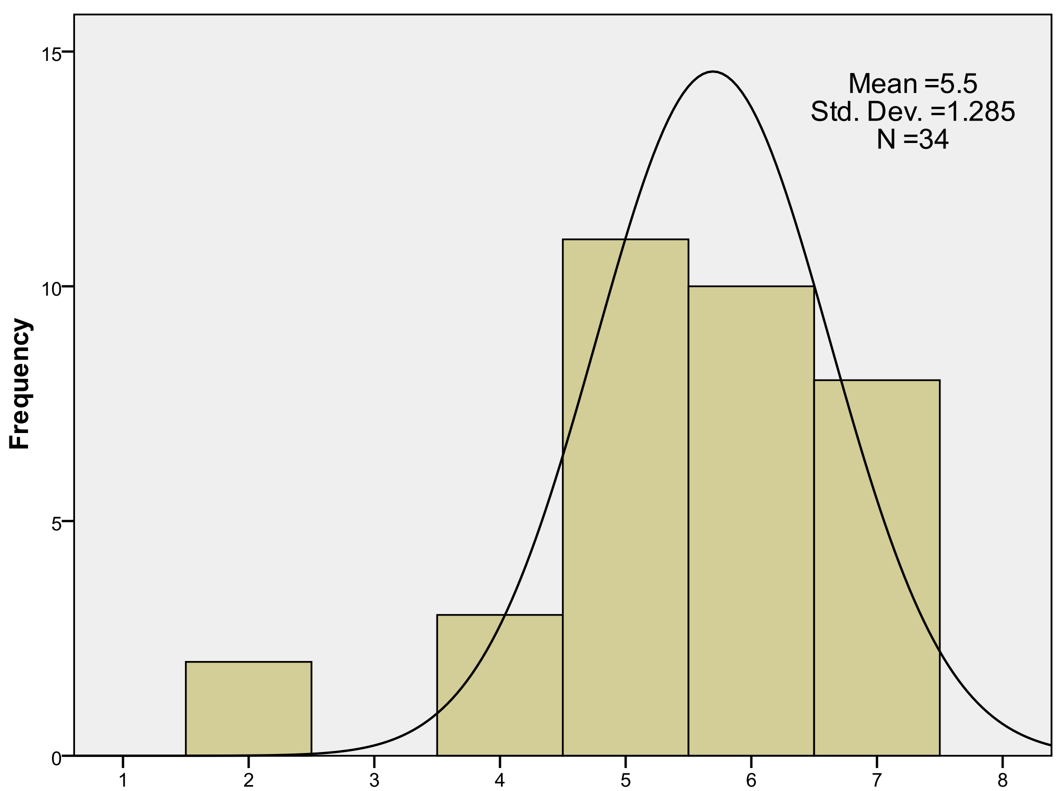


Figure 5-9. Current BIM tools can help formulate LEED strategies.

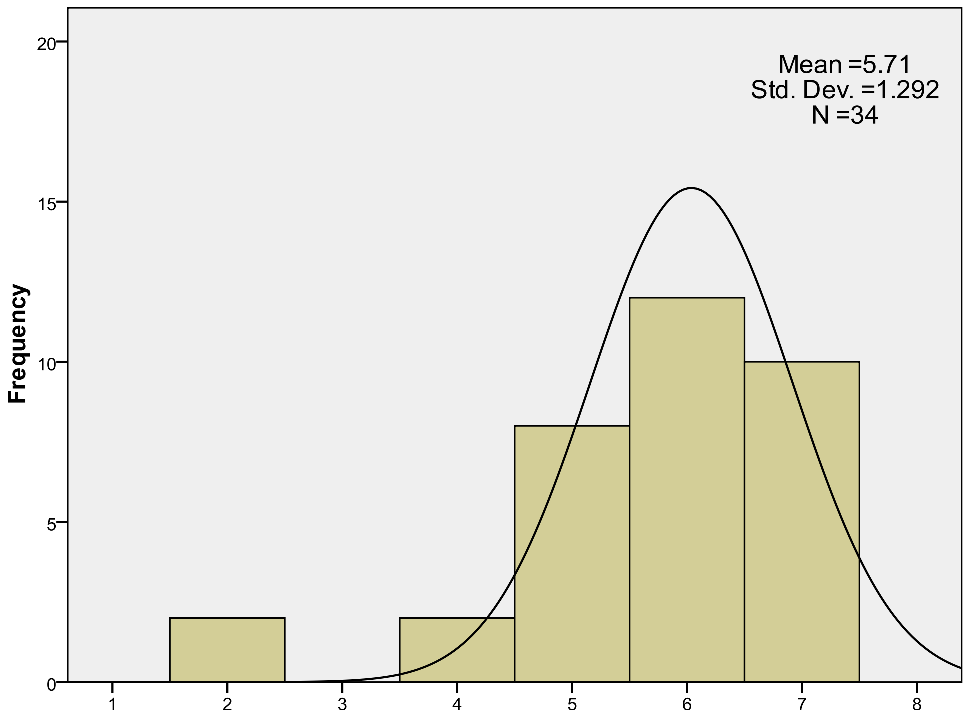


Figure 5-10. Current BIM tools can facilitate the generation and dissemination of design and contract documents.

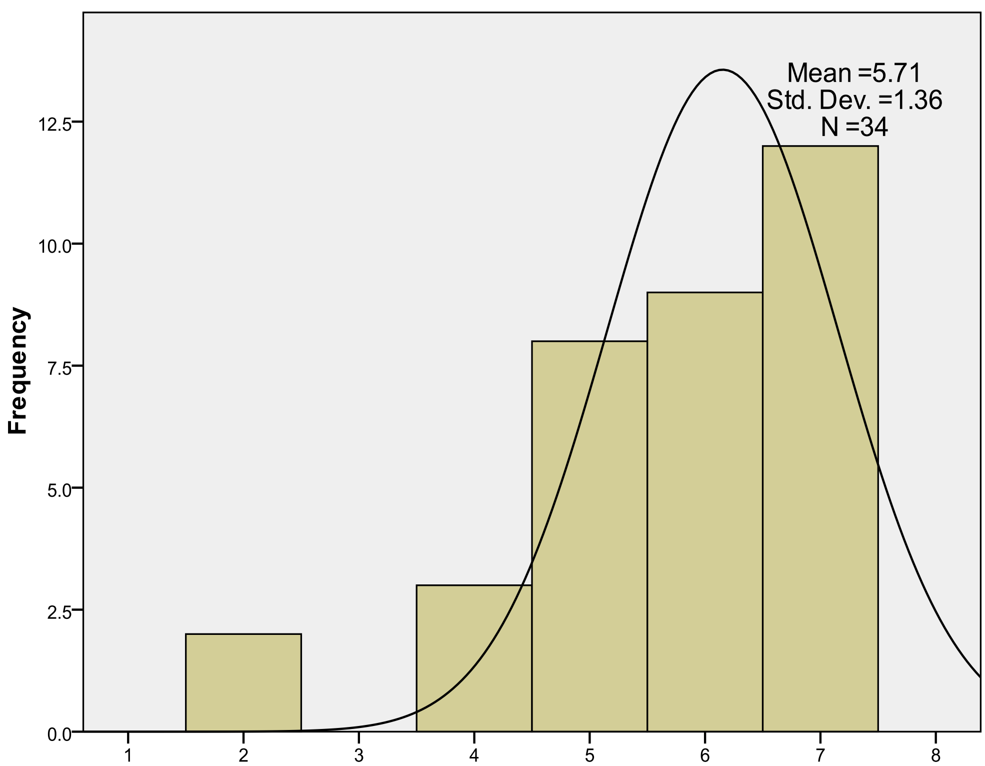


Figure 5-11. Current BIM tools can facilitate communication and information exchange between project members.

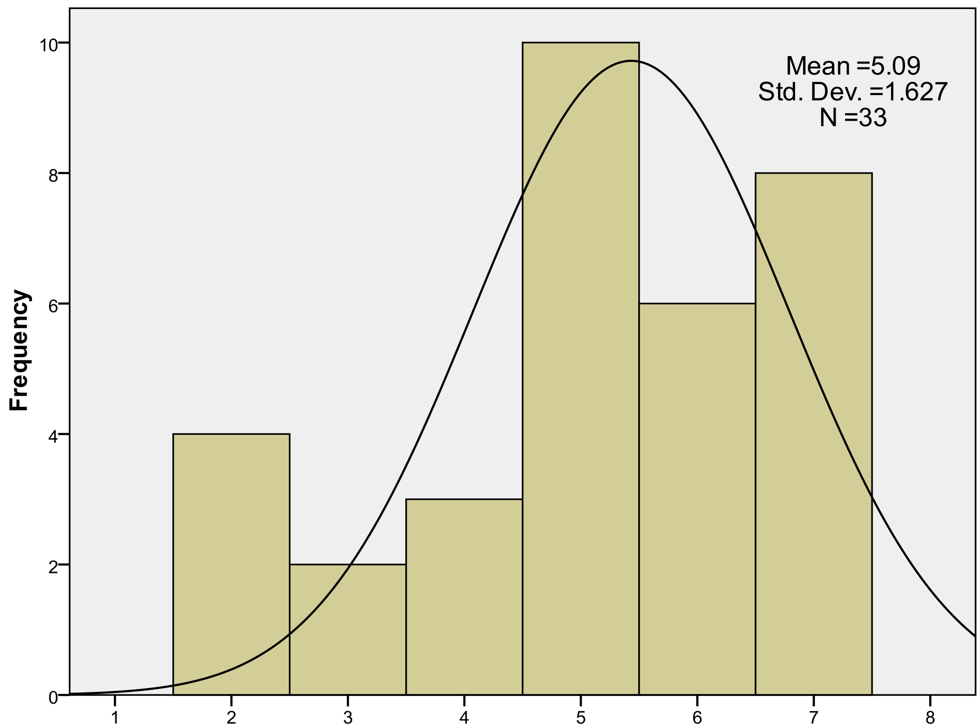


Figure 5-12. Current BIM tools can facilitate certification documentation generation and submission to LEED-Online.

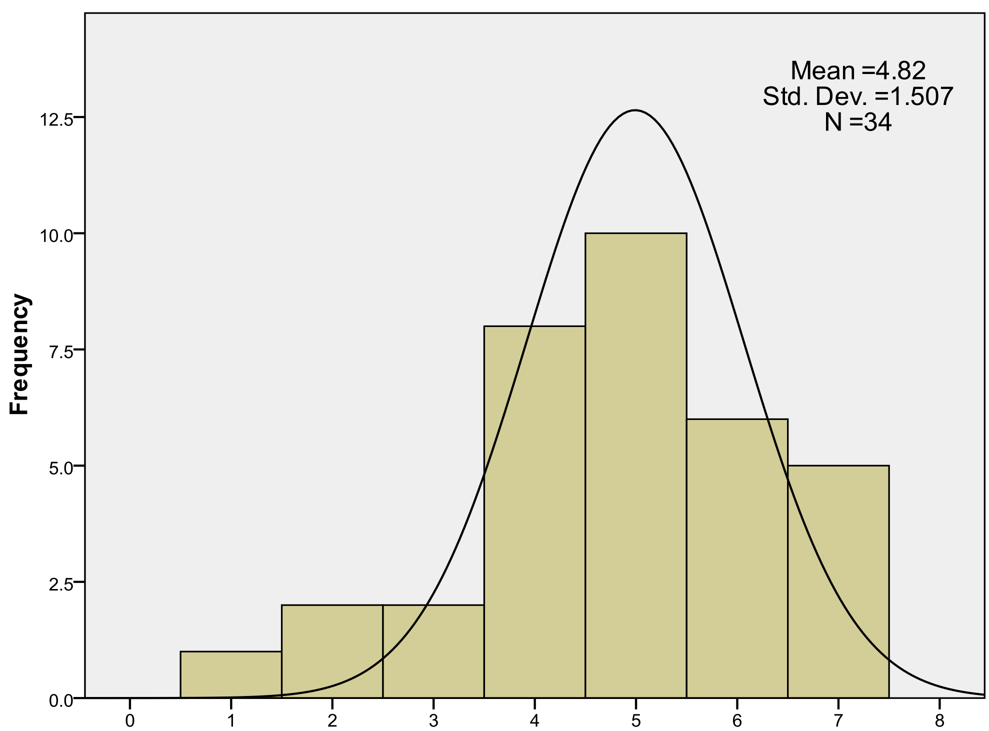


Figure 5-13. Current BIM tools can help reduce upfront cost of pursuing LEED-NC v2.2 certification.

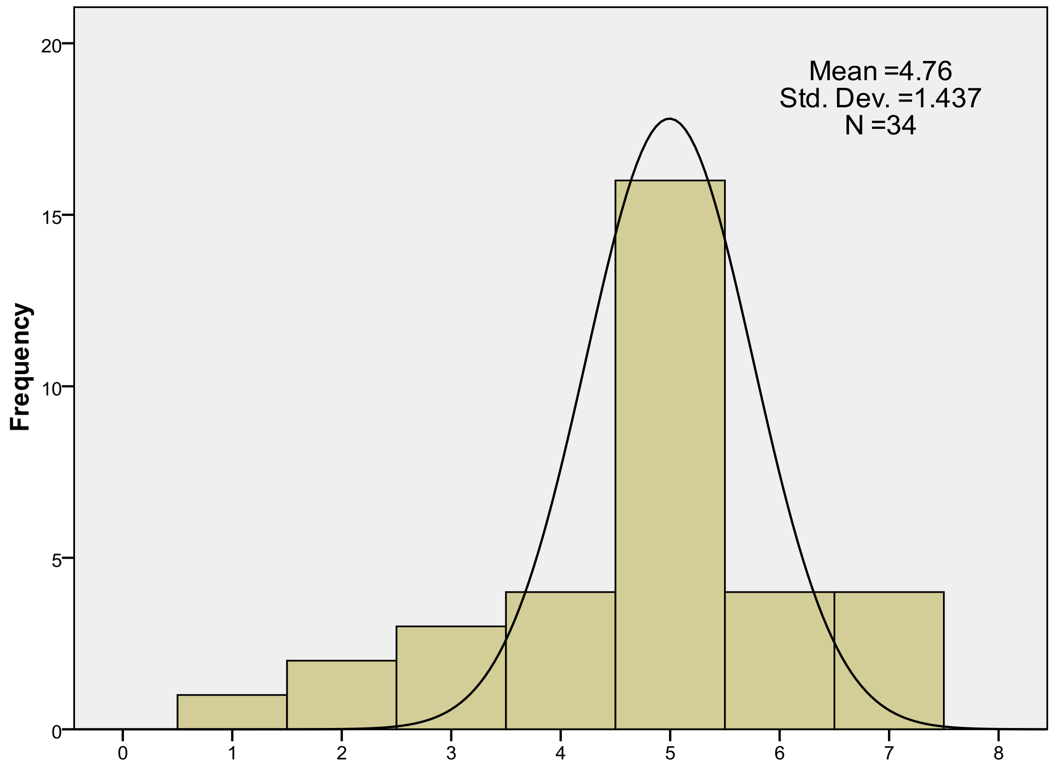


Figure 5-14. Current BIM tools can increase the overall chances of achieving LEED-NC v2.2 certification.

As shown in Figure 5-5, the respondents somewhat disagreed, with a mean score of 3.53, with the sufficiency of current BIM software tools in meeting the LEED-NC v2.2 requirements. Figure 5-6, with a mean score of 3.21, shows that respondents did not think their companies had fully integrated BIM solutions into LEED project delivery. Figure 5-7 shows that they acknowledged the benefits of using BIM at the preconstruction stage in a LEED project (mean score of 4.29). However, a mean score of 3.88 (see Figure 5-8) reveals the participants' doubts about the role of BIM in the construction stage. On the other hand, they were very convinced (mean score> 5.00) about utilizing BIM for their LEED strategy (Figure 5-9) (for instance, review which LEED points were perceived more feasible than others); generating and disseminating better-quality contract documentation (Figure 5-10); creating submittals as required by

LEED certification (Figure 5-12); and improving communication and collaboration between project teams (Figure 5-11). With an average score of 4.82 (see Figure 5-13) the respondents tended to agree that with the assistance of BIM, they could potentially reduce the upfront cost involved in obtaining LEED certification. They were also optimistic (mean score of 4.76) that with the facilitation of BIM the project might have a better chance to get LEED certified (see Figure 5-14).

To summarize this part of the survey, companies should be aware of their unique roles in the AEC industry so as to customize their strategy for BIM implementation in their own business operation. A fundamental goal should be set so as to maximize the benefits derived from the use of BIM applications while simultaneously being cautious to avoid the potential loss attributed to inefficiencies inherent in current BIM technologies. For instance, it is worthwhile for contractors to identify the factors that have diluted the synergies between BIM and LEED at the construction stage, and what action they could take to fix them and generate more benefits from BIM adoption.

Part 2 – Section 2: Feasibility Analysis

The result from Part 2 – Section 1 was helpful in identifying issues that needed to be addressed in the long term to make BIM-LEED integration successful. But for the project teams they were more concerned about whether there were sound solutions to the immediate problems that they came across in the project in regard to the details of the LEED credits. The next set of questions, Part 2 – Section 2 of this survey, addressed the issue of how feasible it is to use “these” BIM solutions to score “those” LEED points. Credits for all seven categories in the LEED-NC 2009 rating system were assigned a numeric value (0 as not applicable while 5 meant most applicable) to indicate the level of applicability when incorporating current BIM solutions to help pursue the corresponding LEED points (see Appendix A). Participants were asked to determine the value based on their experience, knowledge or assumption.

In Category 1 - Sustainable Sites, Credit 8: Light Pollution Reduction credit (SSc8) received the highest mean score of 3.34, while Credit 4: Alternative Transportation (SSc4) received the lowest mean score (1.94). Participants commented that an embedded linkage with GIS in BIM could significantly help the attainment of points in this category. Site vicinity information such as proximity to public transportation, community connectivity, and infrastructure can be easily extracted from local or national GIS sources to help the project team make better informed decisions. Table 5-1 summarizes the scores for Category 1 – Sustainable Sites.

Table 5-1. Applicability levels in Category 1 – Sustainable Sites

		SSp1	SSc1	SSc2	SSc3	SSc4	SSc5	SSc6	SSc7	SSc8
N*	Valid	32	32	32	32	31	32	32	31	32
	Missing	3	3	3	3	4	3	3	4	3
Mean		2.31	2.72	2.69	2.09	1.94	2.88	2.94	3.19	3.34
Std. Deviation		1.575	1.550	1.424	1.376	1.315	1.385	1.190	1.424	1.599

*N = number of responses.

In Category 2 – Water Efficiency, the scores were relatively stable for each credit. Comments from participants suggested that the use of BIM would not necessarily be advantageous over conventional 2D applications such as CAD in terms of improving the performance of water efficiency. Also there were complaints about the complexity of using current BIM software tools for mechanical, electrical and plumbing (MEP) systems in general. Table 5-2 summarizes applicability levels in this category.

In Category 3 – Energy and Atmosphere, best consensus was achieved on the energy performance related credits, Minimum Energy Performance (EAp2, mean score at 3.78) and Optimize Energy Performance (EAc1, mean score at 3.78). Building energy performance had been at the heart of building modeling and simulation research. The capabilities of BIM technologies were enhanced by incorporating geographical and weather data into design consideration to optimize the orientation, massing, daylighting, and natural ventilation, to name a few. It was worth noting that there was an inconsistency between the Fundamental Commissioning of Building Energy Systems (EAp1) with mean score of 3.16 and Enhanced Commissioning (EAc3) with a mean score of 2.59. Building commissioning plays a significant role in ensuring that the completed facility has actually met the design performance and will maintain such performance throughout the building's life cycle. Table 5-3 summarizes the responses in this category.

Table 5-2. Applicability levels in Category 2 – Water Efficiency

		WEp1	WEc1	WEc2	WEc3
N	Valid	32	32	32	32
	Missing	3	3	3	3
Mean		2.78	2.44	2.47	2.72
Std. Deviation		1.211	1.190	1.436	1.224

Table 5-3. Applicability levels in Category 3 – Energy and Atmosphere

		EAp1	EAp2	EAp3	EAc1	EAc2	EAc3	EAc4	EAc5	EAc6
N	Valid	32	32	32	32	32	32	32	32	32
	Missing	3	3	3	3	3	3	3	3	3
Mean		3.16	3.78	2.31	3.78	3.09	2.59	2.44	3.19	2.59
Std. Deviation		1.668	1.289	1.615	1.313	1.445	1.682	1.458	1.575	1.316

In Category 4 – Materials and Resources, most scores fell between 2 and 3 except for Building Reuse (MRc1) with a mean score of 3.44. Submittals for MRc1 required calculation of the reused area of structural building components such as walls, floors and the roof, which could be easily obtained from the BIM model. The key to better applicability of BIM in this category as suggested was to create an imbedded material library customized for an integrated BIM-LEED work environment. For instance, quite a few participants mentioned they would be more willing to pursue MRc4: Recycled Content if an industrial directory that listed local recycled/salvaged material suppliers by zip code was internalized in the database of current BIM software tools. Additionally, some of the respondents again brought up making GIS linkage a built-in function in the building information model in order to streamline the analysis of credits such as MRc5: Regional Materials. Table 5-4 summarizes responses in this category.

Table 5-4. Applicability levels in Category 4 – Materials and Resources

		MRp1	MRc1	MRc2	MRc3	MRc4	MRc5	MRc6	MRc7
N	Valid	32	32	32	32	32	32	32	32
	Missing	3	3	3	3	3	3	3	3
Mean		2.66	3.44	2.16	2.97	2.84	2.41	2.50	2.53
Std. Deviation		1.035	1.294	1.322	1.092	1.370	1.341	1.344	1.391

In Category 5 – Indoor Environmental Quality, participants had distinct opinions on the applicability levels for different credits. IEQc8: Daylight and Views scored a mean of 4.13, while IEQp2: Environmental Tobacco Smoke Control had a mean score of 2.10. As previously discussed, weather data, solar intensity level and building orientation can be incorporated and configured easily in a building information model. Design professionals got better control over the subtleties with the numerous options enabled by current BIM technology to achieve optimal daylighting strategy. Visualization could be enhanced in a well constructed building information model with adequate site details. Clients could virtually see what the building would look like after construction, and make adjustments to their actual view needs in a real-time manner. Green Building Studio and IES<VE> were mentioned by respondents as popular tools in daylight and view design. Table 5-5 summarizes the responses in Category 5.

Table 5-5. Applicability levels in Category 5 – Indoor Environmental Quality

		IEQp 1	IEQp 2	IEQc 1	IEQc 2	IEQc 3	IEQc 4	IEQc 5	IEQc 6	IEQc 7	IEQc 8
N	Valid	31	31	30	30	31	31	31	31	30	31
	Missing	4	4	5	5	4	4	4	4	5	4
Mean		3.06	2.10	2.83	3.30	2.45	3.03	2.74	3.23	3.40	4.13
Std. Deviation		1.526	1.446	1.315	1.179	1.362	1.016	1.264	1.359	1.163	1.258

Category 6: Innovation in Design and Category 7: Regional Priority are quite descriptive in nature. The respondents suggested that the integration of BIM in LEED per se should be regarded as innovative and indicated that they would not mind using it as a marketing tool for their projects. On the other hand, pursuit of points in "LEED Accredited Professional" and identifying "Regional Priorities" did not necessarily involve the use of BIM. Table 5-6 summarizes both Category 6 and Category 7 responses.

Table 5-6. Applicability levels in Categories 6 and 7

		IDc1	IDc2	RPc1
N	Valid	31	30	31
	Missing	4	5	4
Mean		3.68	1.83	2.32
Std. Deviation		1.641	1.802	1.469

Survey Summary

The investigation of user perceptions of the status quo preliminarily benchmarked current BIM solutions and their applicability in LEED projects. It revealed that in spite of acknowledging the great potential of BIM, professionals were apprehensive about its value at the actual construction stage of the LEED project delivery process. They recognized the opportunity to take advantage of BIM technology in pursuit of specific LEED points; nonetheless they indicated that they would not rely exclusively on BIM to compile LEED certification documentation. In addition, some comments from the participants were very constructive for future BIM software development. For instance, more than a few professionals suggested the need for business directory to be built in the BIM authoring tools. This directory could list material suppliers and categorize their products with recycled contents, regional materials, or other LEED-oriented information by zip code. This would greatly promote designers' selection of more environmental friendly products while also contributing to the LEED certification needs. Another highly desirable feature mentioned by the respondents was the linkage to GIS data in the BIM authoring tools. GIS information can be particularly valuable to site selection and the connectivity of the building project to the local community.

Results: Generic Integration Framework

The principle to integrate BIM and LEED certification is straightforward. The requirements of LEED credits should be matched up with the functionalities of BIM solutions. Figure 5-15 describes this intuitive relationship.

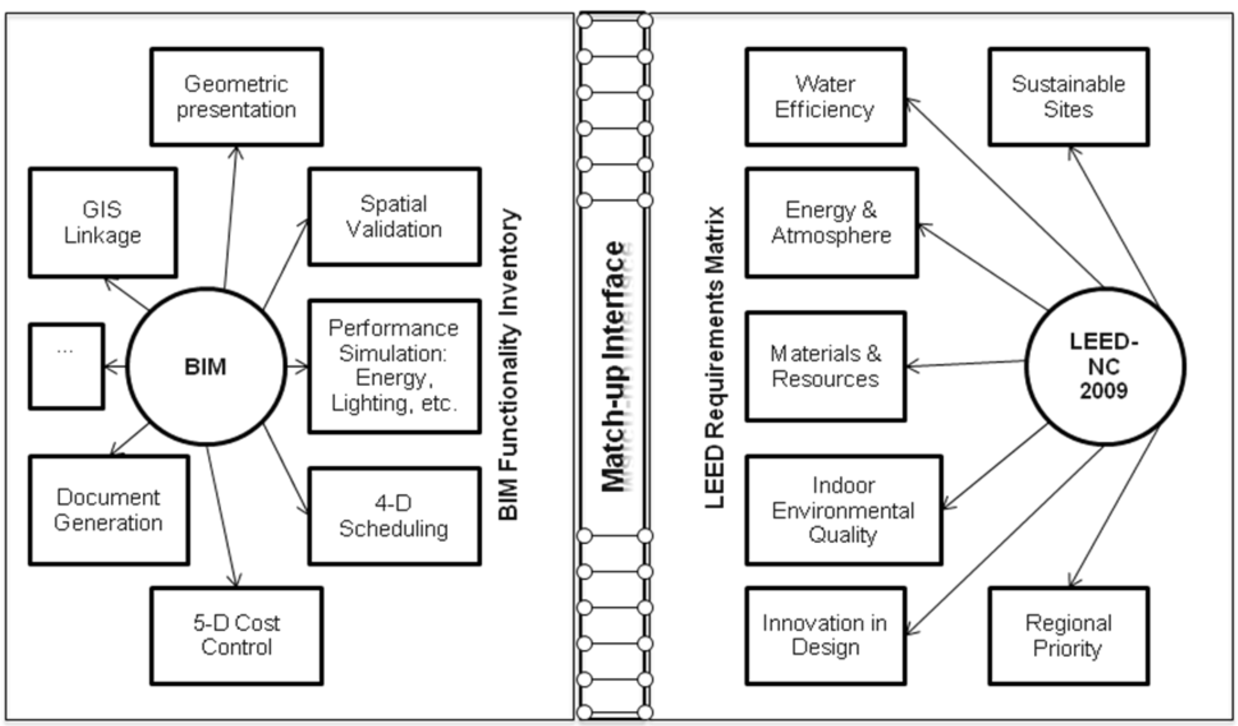


Figure 5-15. Intuitive relationship of the integration framework.

When going into the actual integration process, the LEED rating system is broken down into credits, and eventually the requirements clauses. Each statement of the requirements is either a descriptive request or a quantitative specification. For instance, MRp1- Storage and Collection of Recyclables requires:

> Provide an easily-accessible dedicated area or areas for the collection and storage of materials for recycling for the entire building. Materials must include, at a minimum: paper, corrugated cardboard, glass, plastics and metals. (USGBC 2007)

This is a typical descriptive request. The key words in this request include “easily-accessible”, “dedicated area”, “recycling”, “materials”, “paper”, “corrugated cardboard”, “glass”, “plastics” and “metals”. The descriptive request often involves only “text” type keywords. In contrast, MRc3 – Material Reuse requires:

> Use salvaged, refurbished or reused materials, the sum of which constitutes at least 5% or 10%, based on cost, of the total value of materials on the project. (USGBC 2007)

This is a typical quantitative request. The key words in this request include “salvaged”, “refurbished”, “reused”, “materials”, “5%”, “10%”, “cost”, and “total value”. The quantitative request should at least include one or more “numeric” type keywords.

From the BIM functionality inventory perspective, those functionalities have to be dependent on the building information model or model components. In other words, without the model, those functionalities cannot be checked out, thus they will not be able to be executed. For instance, “schedules” is an important feature that captures comprehensive information (e.g. material property, geometry, count and cost) for a specific category (e.g. doors and windows) of the building information model. If the category was not presented in the model, then the schedule for that particular category will not be able to collect any information. Under certain circumstances, a type of functionality is dependent on certain model components plus the relationship between these components. The relationship can be static (e.g. geometric) or dynamic (e.g. sequencing). The complexity of the match-up between the LEED requirements and the BIM functionalities is illustrated in Figure 5-16. Column A shows a group of indicator type measures embedded in the rating system while Column C shows the building information model broken down into the component level in the popular CSI format. In Revit, every model object is assigned an assembly code defined by the Uniformat system. Accordingly, Column C in Figure 5-16 could be re-arranged into Uniformat.

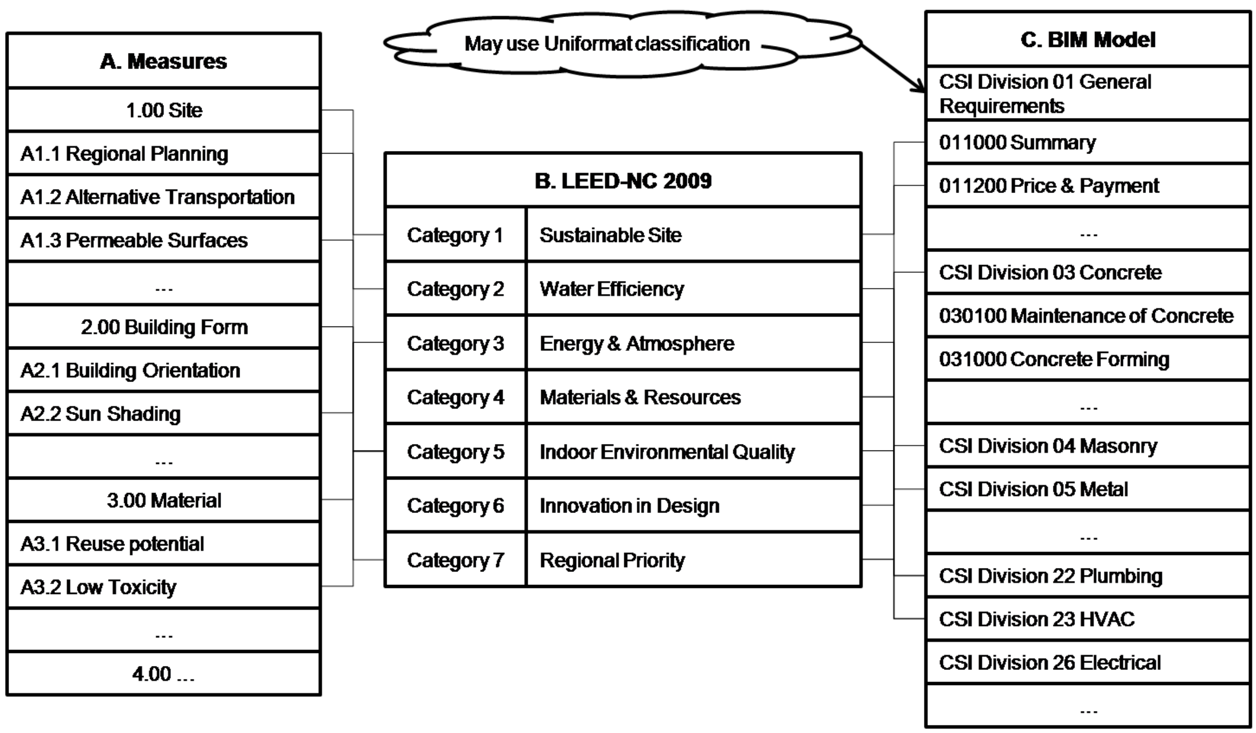


Figure 5-16. Integration framework relationship developed. (Source: adapted from Biswas et al. 2009).

Interpreting LEED Requirements

The following paragraphs perform the analysis of all LEED credits and their requirements by category, mark up the key words, and interpret them into descriptive or quantitative data requests. Starting with LEED v3, the project has to satisfy the

Minimum Program Requirements (MPRs) to be eligible for certification. The MPRs thus become part of the general requirements, and are included in the analysis.

Minimum program requirements

MPRs define the types of buildings that the LEED Green Building Rating Systems were designed to evaluate, and taken together serve three goals: to give clear guidance to customers; to protect the integrity of the LEED program; and to reduce complications that occur during the LEED certification process (GBCI 2009).

"MPR1 – Must comply with environmental laws" stipulates that the LEED project building or space, all other real property within the LEED project boundary, and all project work must comply with applicable federal, state, and local building-related environmental laws and regulations in place where the project is located. This condition must be satisfied from the date of LEED project registration or the commencement of schematic design, whichever comes first, up and until the date that the building receives a certificate of occupancy or similar official indication that it is fit and ready for use.

Table 5-7 illustrates a typical report of the LEED requirement and an interpretation of it. The key words have been identified and summarized. This is a typical "Descriptive request". The most suitable data type is either a "Yes or No" Boolean type or "Text" type. Due to the similarity of the rest of the MPRs, the detailed process of interpreting them will be skipped. The results are summarized in the ensuing Tables 5-7 to 5-13.

Table 5-7. Interpreting report of MPR-1

Item	Description
LEED Category	MPR-1: Must Comply with Environmental Laws
Key Words	project building or space, real property, project boundary, project work, project registration, schematic design, certificate of occupancy
Request Type	Descriptive
Proposed Data Type	Yes or No; Text
Proposed Submittal	Checklist; LEED Online template; Attachments;

Table 5-8. Interpreting report of MPR-2

Item	Description
LEED Category	MPR-2: Must be a Complete, Permanent Building or Space
Key Words	permanent location, existing land, commercial, institutional, or high-rise residential, entirety
Request Type	Descriptive
Proposed Data Type	Yes or No; Text
Proposed Submittal	Checklist; LEED Online template; Attachments

Table 5-9. Interpreting report of MPR-3

Item	Description
LEED Category	MPR-3: Must use a Reasonable Site Boundary
Key Words	all contiguous land, normal building operations, no gerrymandering
Request Type	Descriptive
Proposed Data Type	Yes or No; Text
Proposed Submittal	Checklist; LEED Online template; Attachments

Table 5-10. Interpreting report of MPR-4

Item	Description
LEED Category	MPR-4: Must Comply with Minimum Floor Area Requirements
Key Words	minimum of 1,000 square feet, gross floor area
Request Type	Quantitative
Proposed Data Type	Numeric; Logical
Proposed Submittal	Calculation; LEED Online template

Table 5-11. Interpreting report of MPR-5

Item	Description: Must Comply with Minimum Occupancy Rates
LEED Category	MPR-5
Key Words	1 or more Full Time Equivalent occupants, annual average
Request Type	Quantitative
Proposed Data Type	Numeric; Logical
Proposed Submittal	Calculation; LEED Online template

Table 5-12. Interpreting report of MPR-6

Item	Description
LEED Category	MPR-6: Must Commit to Sharing Whole-building Energy and Water Usage Data
Key Words	actual whole-project energy, water usage data, at least 5 years, supplying information, regular basis, free, accessible, secure, online tool, collection of information, service or utility providers
Request Type	Descriptive
Proposed Data Type	Yes or No; Text
Proposed Submittal	Checklist; LEED Online template; Attachments

Table 5-13. Interpreting report of MPR-7

Item	Description
LEED Category	MPR-7: Must Comply with a Minimum Building Area to Site Area Ratio
Key Words	gross floor area, project building, no less than 2%, gross land area, project boundary
Request Type	Quantitative
Proposed Data Type	Numeric; Logical
Proposed Submittal	Calculation; LEED Online template

LEED categories

There are 5 major environmental categories (SS, WE, EA, MR and IEQ) in the LEED-NC 2009 rating system, plus 2 supplemental categories (ID and RP). As reviewed previously, each LEED category consists of several credits with a certain number of points assigned. Meanwhile compliance with one or more prerequisites is mandatory without any point attainable for each category except for the Innovation and Design (ID) and Regional Priorities (RP). Due to the diversity of building types, geoclimatic factors and owner's project requirements, the LEED rating system allows a certain level of flexibility to the project team by providing compliance options for some credits. The compliance options constitute the requirements for the credit, and enable the project team to satisfy the credit with multiple choices. Depending on the level of complexity, one option may be worth more points than others. So the project team has to decide what tradeoff to make when pursuing certain LEED points, based on factors such as cost, availability of resources and technology readiness, to name a few.

The requirements interpreting process of the actual LEED credits is similar to that in the MPRs. Extra care needs to be taken for the submittal part. Unlike the MPRs, the submittals for the LEED credits are much more complicated. There are actually two type of requirements interpretation. The first type is for the credit requirements and the second is for the submittal requirements. The interpretation of the credit requirements deals with the data request to achieve compliance while the interpretation of submittal requirements aims to demonstrating the achieved compliance. Tables 5-14 to 5-16 exemplify three different scenarios in the interpretation process:

- Table 5-14 deals with the Prerequisites of LEED credits;
- Table 5-15 deals with Credits without Options; and
- Table 5-16 deals with Credits with Options.

Table 5-14. Prerequisite interpretation report of SSp1

Item	Description
LEED Category	SSp1: Construction Activity Pollution Prevention
Requirements Key Words	2003 EPA construction general permit, local standards, National Pollutant Discharge Elimination System (NPDES) program
Request Type	Descriptive
Proposed Data Type	Yes or No; Text
Submittal Requirements	Project drawings; Confirmation of NPDES compliance; Narrative; LEED-Online template
Submittal Data Type	Image; Boolean; Text

Table 5-15. Credit (without Option) interpretation report of SSc1

Item	Description
LEED Category	SSc1: Site Selection
Requirements Key Words	do not develop, prime farmland, lower than 5 feet above the elevation of the 100-year flood, habitat for federal or state threatened or endangered lists, 100 feet of any wetlands, undeveloped land that is within 50 feet of a water body, public parkland
Request Type	Descriptive and quantitative
Proposed Data Type	Yes or No;
Submittal Requirements	Confirm compliance with criteria; Narrative; LEED-Online template
Submittal Data Type	Image; Boolean; Text

Table 5-16. Credit (with Option) interpretation report of SSc2

Item	Description
LEED Category	SSc2: Development Density & Community Connectivity
Requirements Key Words	Option 1: development density, previously developed site, minimum density of 60,000 square feet per acre net; Option 2: previously developed site,1/2 mile, average density of 10 units per acre net, 10 basic services, pedestrian access
Request Type	Descriptive and quantitative
Proposed Data Type	Yes or No; Numeric
Submittal Requirements	Option 1: Site vicinity plan; Site/Building area; Development density; LEED-Online template Option 2: Site vicinity plan; Site/Building area; List of business; Narrative; LEED-Online template
Submittal Data Type	Image; Boolean; Numeric; Text

A complete interpretation report for the LEED MR category is shown in Tables 5-17 to 5-25. The results identify key words in a LEED credit requirement description and determine if descriptive or quantitative data are needed. Then the submittal requirement of this credit is also analyzed and interpreted, following the same methodology.

Table 5-17. Prerequisite interpretation report of MRp1

Item	Description
LEED Category	MRp1: Storage and Collection of Recyclables
Requirements Key Words	easily-accessible, dedicated area, recycling, minimum, paper, corrugated cardboard, glass, plastics and metals
Request Type	Descriptive and quantitative
Proposed Data Type	Yes or No; Numeric
Submittal Requirements	Recycling plan; Floor plan/site plan with recycling storage area; LEED Online template
Submittal Data Type	Image; Boolean; Numeric; Text

Table 5-18. Credit interpretation report of MRc1.1

Item	Description
LEED Category	MRc1.1: Building Reuse - Structural
Requirements Key Words	existing building structure, envelope, area percentage, 55%, 75%, 95%, addition less than 2 times square footage of existing building
Request Type	Descriptive and quantitative
Proposed Data Type	Numeric; Logical
Submittal Requirements	Table of existing and reused square footage; For addition, confirm meeting square footage requirements; LEED Online template
Submittal Data Type	Numeric; Logical; Text

Table 5-19. Credit interpretation report of MRc1.2

Item	Description
LEED Category	MRc1.2: Building Reuse – Non-structural
Requirements Key Words	existing interior nonstructural elements, at least 50% by area, addition less than 2 times square footage of existing building
Request Type	Descriptive and quantitative
Proposed Data Type	Numeric; Logical
Submittal Requirements	Table of existing and reused square footage; For addition, confirm meeting square footage requirements; LEED Online template
Submittal Data Type	Numeric; Logical; Text

Table 5-20. Credit interpretation report of MRc2

Item	Description
LEED Category	MRc2: Construction Waste Management
Requirements Key Words	recycle and/or salvage, nonhazardous, construction and demolition debris, construction waste management plan, 50%, 75%, weight or volume
Request Type	Descriptive and quantitative
Proposed Data Type	Numeric; Text
Submittal Requirements	Calculation tables; Location of landfill/receiving agents; Construction waste management plan; LEED Online Template
Submittal Data Type	Numeric; Text

Table 5-21. Credit interpretation report of MRc3

Item	Description
LEED Category	MRc3: Material Reuse
Requirements Key Words	salvaged, refurbished or reused materials, permanently installed, 5% or 10%, based on cost, total value of materials, or 45% of total construction cost
Request Type	Descriptive and quantitative
Proposed Data Type	Numeric; Text
Submittal Requirements	Calculation tables; Reuse strategy; LEED Online template
Submittal Data Type	Numeric; Text

Table 5-22. Credit interpretation report of MRc4

Item	Description
LEED Category	MRc4: Recycled Content
Requirements Key Words	recycled content, postconsumer, 1/2 of the preconsumer, 10% or 20%, based on cost, total value of materials, or 45% of total construction cost
Request Type	Descriptive and quantitative
Proposed Data Type	Numeric; Text
Submittal Requirements	Calculation tables; Product vendors and cutsheets; LEED Online template
Submittal Data Type	Numeric; Text

Table 5-23. Credit interpretation report of MRc5

Item	Description
LEED Category	MRc5: Regional Materials
Requirements Key Words	extracted, harvested or recovered, manufactured,500 miles, 10% or 20%, based on cost, total value of materials, or 45% of total construction cost, fraction percentage by weight
Request Type	Descriptive and quantitative
Proposed Data Type	Logical; Numeric; Text
Submittal Requirements	Confirmation on regional materials, Calculation tables; Product vendors and cutsheets; LEED Online template
Submittal Data Type	Logical; Numeric; Text

Table 5-24. Credit interpretation report of MRc6

Item	Description
LEED Category	MRc6: Rapidly Renewable Materials
Requirements Key Words	rapidly renewable, 2.5% based on cost, total value of materials, or 45% of total construction cost, 10-year or shorter cycle
Request Type	Descriptive and quantitative
Proposed Data Type	Logical; Numeric; Text
Submittal Requirements	Confirmation on rapidly renewable materials, Calculation tables; Product vendors and cut sheets; LEED Online template
Submittal Data Type	Logical; Numeric; Text

Table 5-25. Credit interpretation report of MRc7

Item	Description
LEED Category	MRc7: Certified Wood
Requirements Key Words	50% , based on cost, value of wood based materials, permanently installed, FSC, assembly percentage based on weight, volume or cost
Request Type	Descriptive and quantitative
Proposed Data Type	Logical; Numeric; Text
Submittal Requirements	FSC/COC compliance; Calculation tables; Product vendors and invoices; LEED Online template
Submittal Data Type	Logical; Numeric; Text

Screening the BIM Functionality Inventory

The functionality inventory of the Revit suite and supplemental applications including GBS, Ecotect from Autodesk, and GIS, Google Earth, etc. have been briefly introduced in previous paragraphs. With the LEED requirements interpreted into data requests, it is time to match up these requests and those functionalities. Again, LEED Materials and Resources will be used as an example. Basically, as previously explained, for each Prerequisite or Credit, there are two kinds of data requests, one for actual compliance and one for demonstrating the compliance, which is the submittal. Tables 5-26 to 5-34 illustrate the process to explore suitable functionality for compliance and submittal requests respectively.

Table 5-26. Functionality screening for MRp1: Storage and Collection of Recyclables

BIM Solution	Functionality vs. Compliance Request	Functionality vs. Submittal Request
Revit	Site plan/Floor plan (2D/3D); Decals for recyclables;	Site plan/Floor plan; Area calculation (quantity takeoff)

Table 5-27. Functionality screening for MRc1.1: Building Reuse - Structural

BIM Solution	Functionality vs. Compliance Request	Functionality vs. Submittal Request
Revit	Floor plan by phases (demolish + new construction); Area takeoff by phases for structural components	Schedules/quantities report on structural components by phases

Table 5-28. Functionality screening for MRc1.2: Building Reuse - Nonstructural

BIM Solution	Functionality vs. Compliance Request	Functionality vs. Submittal Request
Revit	Floor plan by phases (demolish + new construction); Area takeoff by phases for non structural interior components	Schedules/quantities report on non structural interior components by phases

Table 5-29. Functionality screening for MRc2: Construction Waste Management

BIM Solution	Functionality vs. Compliance Request	Functionality vs. Submittal Request
Revit	Floor plan by phases (demolish + new construction); Multi-category material takeoff by phases (volume +density factor)	Schedules/quantities report on multi-category material takeoff by phases (volume or weight)

Table 5-30. Functionality screening for MRc3: Material Reuse

BIM Solution	Functionality vs. Compliance Request	Functionality vs. Submittal Request
Revit	Shared parameter* (tag material as reused); Material takeoff and pricing	Schedules/quantities report on reused materials; Pricing (material cost only) report

* Shared parameters are parameters that can be added to families or projects and then share with other families and projects. They give the ability to add specific data that is not already predefined in the family file or the project template.

Table 5-31. Functionality screening for MRc4: Recycled Content

BIM Solution	Functionality vs. Compliance Request	Functionality vs. Submittal Request
Revit	Shared parameter (tag material as postconsumer or preconsumer); Material takeoff and pricing	Schedules/quantities report on recycled contents; Pricing (material cost only) report

Table 5-32. Functionality screening for MRc5: Regional Materials

BIM Solution	Functionality vs. Compliance Request	Functionality vs. Submittal Request
Revit	Shared parameter (tag material as regional; zip code); Material takeoff and pricing	Schedules/quantities report on regional materials; Pricing (material cost only) report

Table 5-33. Functionality screening for MRc6: Rapidly Renewable Materials

BIM Solution	Functionality vs. Compliance Request	Functionality vs. Submittal Request
Revit	Shared parameter (tag material as rapidly renewable); Material takeoff and pricing	Schedules/quantities report on regional materials; Pricing (material cost only) report

Table 5-34. Functionality screening for MRc7: Certified Wood

BIM Solution	Functionality vs. Compliance Request	Functionality vs. Submittal Request
Revit	Shared parameter (tag material as FSC certified); Material takeoff and pricing	Schedules/quantities report on regional materials; Pricing (material cost only) report

Integration Framework Summary

The integration framework is basically established on the basis of the LEED requirements interpretation and the BIM functionality screening. Table 5-35 summarizes this framework in the tabular format.

Table 5-35. Integration framework summary

LEED – NC 2009	Autodesk Products	Non-Autodesk Products	Notes
MPR-1	Revit: Project information		
MPR-2	Revit: Project information		
MPR-3	Revit: Site plan		
MPR-4	Revit: Floor plan		
MPR-5	Revit: Floor plan + Shared parameter (FTE)		
MPR-6	FMDesktop	FM: Systems	
MPR-7	Revit: Site plan + Floor plan		
SSp1	Civil 3D; Revit: Site plan		
SSc1	Civil 3D; Revit: Site plan + KML file	ArcGIS: Local GIS data	
SSc2		ArcGIS: Local GIS data or Google Map	
SSc3	Revit: Project information		
SSc4.1	Revit: Shared parameter (Zip code)	ArcGIS: Local GIS data or Google Map	
SSc4.2	Revit: Site plan + Floor plan; Shared parameter (FTE)		
SSc4.3	Revit: Site plan with parking components; Shared parameter (FTE)		
SSc4.4	Revit: Site plan with parking components; Shared parameter (FTE)		
SSc5.1	Revit: Site plan		
SSc5.2	Revit: Site plan with use of property line; Building layout plan		
SSc6.1	Revit: Site plan; Civil 3D		
SSc6.2	Revit: Site plan; Civil 3D		
SSc7.1	Revit: Site plan with landscaping + parking; Shared parameter (SRI)		

Table 5-35. Continued.

LEED – NC 2009	Autodesk Products	Non-Autodesk Products	Notes
SSc7.2	Revit: Roof plan; Shared parameter (SRI)		
SSc8	Revit: Site plan with exterior lighting	IES<VE>: RadianceIES	
WEp1	Revit: Plumbing fixture schedules (baseline case + design case); Shared parameters (Flowrate + FTE). GBS: Water consumption analysis		
WEc1	Revit: Site plan with landscaping. GBS: Water consumption analysis		
WEc2	Revit: Plumbing fixture schedules (baseline case + design case); Shared parameters (Flowrate + FTE). GBS: Water consumption analysis		
WEc3	Revit: Plumbing fixture schedules (baseline case + design case); Shared parameters (Flowrate + FTE). GBS: Water consumption analysis		
EAp1	Revit: As-built model + Product information		Very limited
EAp2	Revit: Model geometry, rooms, spaces and zones; GBS: Energy simulation	IES<VE>: Energy simulation	
EAp3	Revit: Product information; Shared parameters (LCGWP+LCODP)		Very limited
EAc1	Revit: Model geometry, rooms, spaces and zones; GBS: Energy simulation	IES<VE>: Energy simulation	
EAc2	GBS: Energy simulation data	IES<VE>: Energy simulation data	Very limited
EAc3	Revit: As-built model + Product information		Very limited
EAc4	Revit: Product information; Shared parameters (LCGWP+LCODP)		Very limited
EAc5	Revit: MEP products schedule		Very limited
EAc6	GBS: Energy simulation data	IES<VE>: Energy simulation data	Very limited
MRp1	Revit: Site plan with area designation		

Table 5-35. Continued.

LEED – NC 2009	Autodesk Products	Non-Autodesk Products	Notes
MRc1.1	Revit: Floor plan + Material takeoff by phases (Demolition and New construction)		Compute Area
MRc1.2	Revit: Floor plan + Material takeoff by phases (Demolition and New construction)		Compute Area
MRc2	Revit: Floor plan + Material takeoff by phases (Demolition and New construction)		Compute Volume or Weight
MRc3	Revit: Shared parameter (Reuse) + Material takeoff and Pricing (material cost only)		Compute Cost
MRc4	Revit: Shared parameters (Post-consumer and Pre-consumer) + Material takeoff and Pricing (material cost only)		Compute Cost
MRc5	Revit: Shared parameter (Regional or Zip code) + Material takeoff and Pricing (material cost only)		Compute Cost
MRc6	Revit: Shared parameter (Rapidly Renewable) + Material takeoff and Pricing (material cost only)		Compute Cost
MRc7	Revit: Shared parameter (FSC) + Material takeoff and Pricing (wood products only)		Compute Wood Cost only
IEQp1	Revit: Space schedule with CFM		Limited
IEQp2	Revit: Floor plan with designated area		Limited
IEQc1			Not Applicable
IEQc2	Revit: Space schedule with CFM		Limited
IEQc3			Not Applicable
IEQc4	Revit: Tag materials with shared parameter (VOCs)		Need manufacturer information
IEQc5	Revit: Floor plan (show entryway design)		Limited
IEQc6.1	Revit: Electrical plan		
IEQc6.2	Revit: Electrical plan + Operable window schedule		
IEQc7.1			Not Applicable
IEQc7.2			Not Applicable

Table 5-35. Continued.

LEED – NC 2009	Autodesk Products	Non-Autodesk Products	Notes
IEQc8.1	Revit: Shared parameters (VLT and WFR); GBS: Daylighting and View analysis; Ecotect: Solar analysis;	IES<VE>: Daylighting and View analysis	
IEQc8.2	Ecotect: Daylighting analysis; 3dsMax: view design		
IDc1	BIM as education tools	BIM as education tools	No definitive approach
IDc2	Revit: Project parameter (LEED-AP)		
RP1	Revit: Shared parameter (Zip Code)		

Results: Revit – LEED Application Model

The integration framework creates the foundation for the Revit – LEED application model. As the BIM solutions keep advancing, this framework will need updating and will evolve accordingly. The application model is LEED project delivery oriented, and the one and only goal is to achieve the LEED certification. Critical stages to be covered by the application model include:

- **Project Planning:** the major concern for the model at this stage is the owner's commitment to LEED. Without this commitment, there is no need to execute this application model at all;

- **Design Charette:** a major task here is formulating the LEED strategy. The owner and the project team need to figure out which level of certification (literally the first decision is which LEED rating system to use but here by default is the LEED – NC 2009 system) the project is looking for; how many LEED points are desirable; which credits to go after and why; preliminary solutions to achieve these LEED points, etc. A premium tool to use at this stage is the LEED check list;

- **Design Development:** obviously, this is the most critical stage in preconstruction. The biggest concern is how to make sure the designers are informed about the LEED requirements, which is often referred as the LEED oriented design. Providing assistance to designers thus becomes a key function the application model should possess. It is also the stage when the design-type LEED credits should be analyzed. Lots of critical design configuration analysis including energy simulation, solar design, daylighting and view design, and water consumption should be done at this stage;

- **Bidding:** although the Revit – LEED application model does not directly involve in the bidding process, the created building information model can help generate contract documentation and conduct constructability analysis;
- **Construction:** two major tasks in this stage of the application model include dealing with the construction-type LEED credits and preparing submittals for pursued LEED points. This is basically the documentation management stage; and
- **LEED Certification Application:** at this stage, all the required LEED Online templates and supplemental submittals should have been completed and submitted to USGBC for review.

As introduced in the methodology part, the Revit – LEED application model consists of two major modules: the design assistance module and the certification management module. The contents, structure, function and applicable stages of this application model are shown in Figure 5-17.

In the course of developing the two modules of the application model, it was observed that with some creative combination, existing features in Revit could be manipulated to provide designers and contractors with new functionalities. Revit by nature is an authoring tool while the project delivery on the other hand is a much more complex management process. How to develop an interface between the Revit platform and critical project management issues in the application model becomes another challenge. The following sections attempt to provide a more in-depth description of developing the two modules of the proposed application model. In determining the needs of the LEED project team, opinions were obtained from project managers and LEED APs in local Gainesville area through face to face interviews, and were incorporated in the model development.

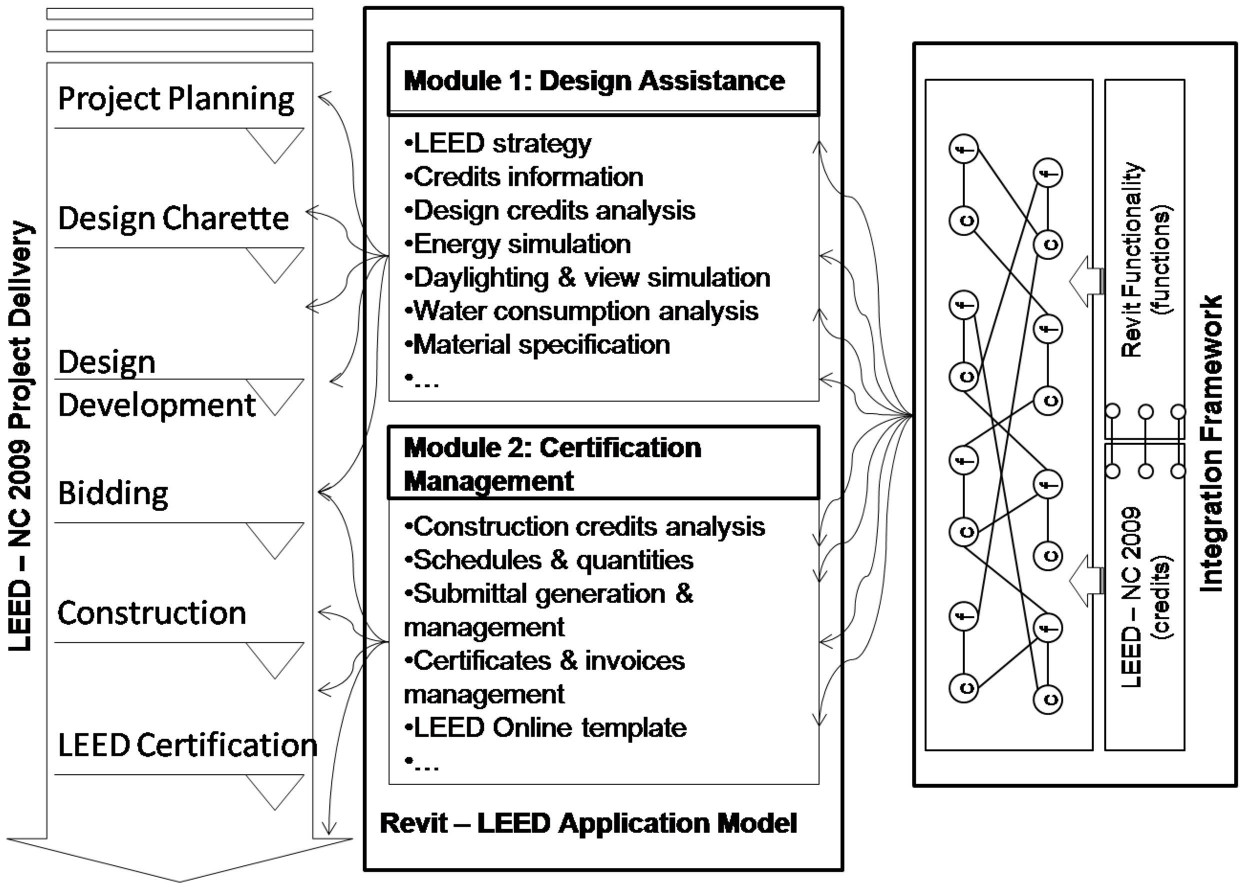


Figure 5-17. Execute Revit – LEED application model in project delivery.

Module 1: Design Assistance

The most fundamental design assistance for a LEED project is to keep the architects and engineers aware of the requirements of the LEED rating system. It is unrealistic to expect that all designers are familiar with LEED, let alone the requirements details for specific credits. Admittedly, the LEED reference guide could help with this. However, it works much better if the desirable LEED knowledge is integrated into the Revit platform so that the designers can literally be "learning while designing".

Before the design process starts, the LEED strategy should be formulated and disseminated to the whole project team. Designers need to ensure that the targeted LEED credits have been taken into account when creating the building information model. As the LEED strategy keeps updating in conformity with the most recent project information, so does the LEED credits status. The LEED strategy is always the bottom line of the project and all team members should be on the right track to the eventual project goal set up in the strategy. Again, a most productive manner to integrate this strategy is to make it part of the Revit platform.

Through interviews with a project administrator (who was also a LEED AP) on some local LEED projects in Gainesville, Florida, some meaningful issues were brought up. A highlighted one was about the material specification, which had actually been touched upon when analyzing the survey results. Lots of contractors have difficulties in finding the appropriate material suppliers since they are not knowledgeable which manufacturers' products have recycled contents; which vendors sell salvaged materials; which suppliers' products are regional; or which wood products are FSC certified. Besides, they may also have no sources for such information either. Consequently, a yellow-page type directory that captures LEED oriented material suppliers and manufacturers could be a very valuable feature for both designers and contractors.

LEED strategy and Revit template

The project template in Revit is a handy tool that can be customized to the needs of specific project types. For the Revit – LEED application model, a LEED – NC 2009 project template is developed. This template is based on the LEED – NC v2.2 template provided by Haynes (2008). Figure 5-18 is the screen shot of the LEED – NC 2009 template. In comparison with indigenous Revit templates, the customized LEED template provides extra features including:

- A built-in LEED checklist that the project team could use as a starting point for the LEED strategy, with fields such as “points achievable” and “points attempted”, the checklist will reflect the targeted LEED certification level;

- A collection of LEED credit sheets that the project could put relevant “views” (floor plan, elevation plan or section plan, etc. are called views in Revit) on to be referenced by the contractors in construction. With as-built information feeding back into the building information model, those sheets of “views” will become important submittals to the LEED certification review process; and

- In order to guarantee the integrity of the LEED checklist, the “points validity” column marks up the erroneously attempted points in red. Obviously, it is not possible to achieve more points than the maximum achievable points for each category.

The detailed steps to create this LEED template are similar to creating ordinary “Schedules and Quantities” in Revit. All the LEED credit sheets are ordinary Revit drawing sheets with customized “Titleblock” features. Appendix B gives a step-by-step guide to create a LEED-NC 2009 template from scratch.

LEED knowledge and Revit API

Since the LEED rating system and all the credits information are completely external to the Revit environment, it is nearly impossible to count on existing functionalities to achieve the goal of integrating the desired LEED knowledge for the designers. The Revit API provides the solution to internalize external applications into the Revit platform. As specified by the Revit 2010 API Developer’s Guide (Autodesk 2009), using the API, developers can:

- Gain access to model graphical data;

- Gain access to model parameter data;

- Create, edit, and delete model elements like floors, walls, columns, and more; Create add-ins to automate repetitive tasks;

- Integrate applications into Revit-based vertical products. Examples include linking an external relational database to Revit or sending model data to an analysis application;

- Perform analysis of all sorts using BIM; and

- Automatically create project documentation.

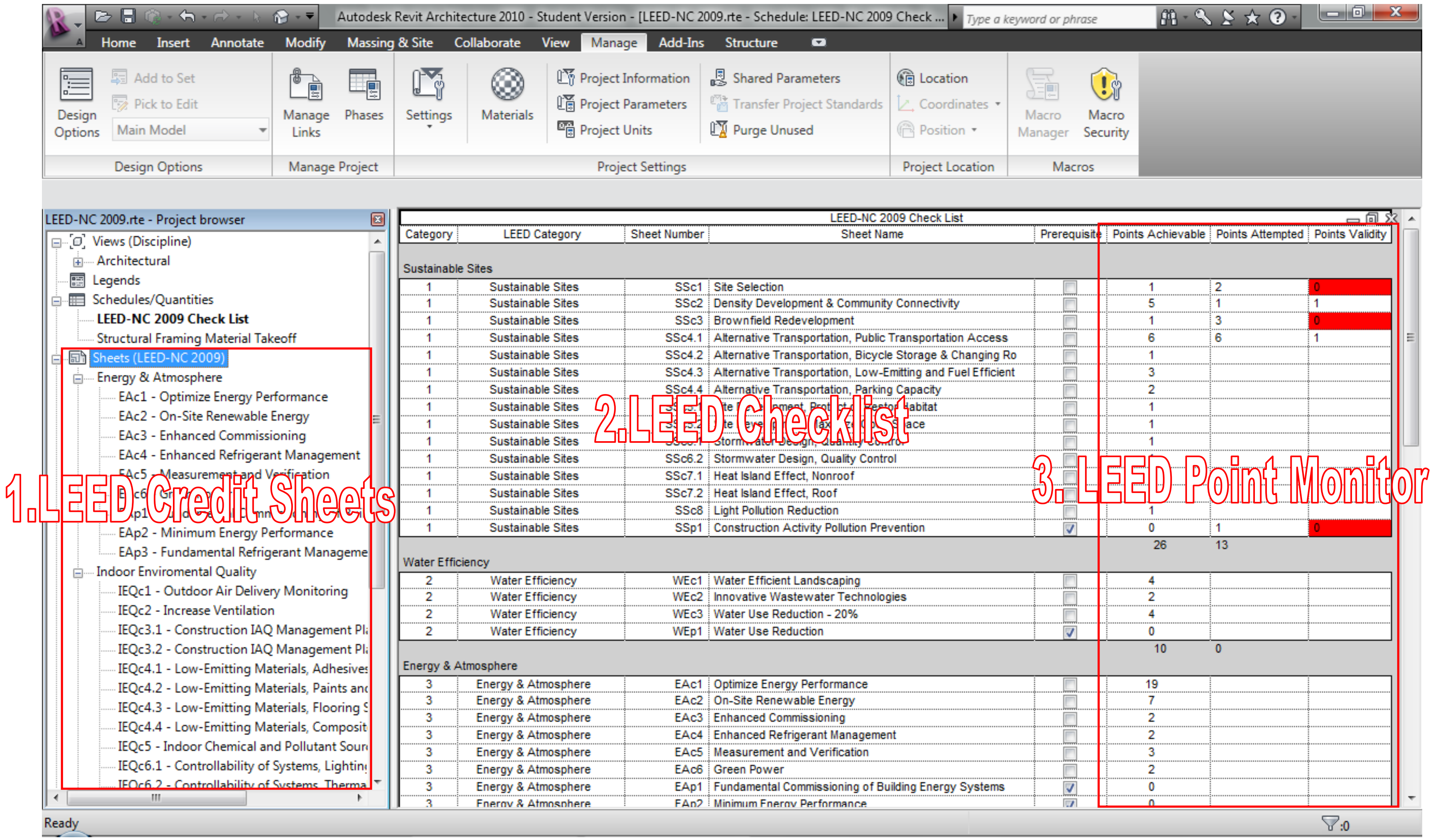


Figure 5-18. The LEED – NC 2009 Revit project template. (Source: developed on basis of Haynes 2008).

The Revit API is compatible with any Microsoft .NET compliant language including Visual Basic.NET, C#, and C++/CLI. To create a Revit API based add-in, the developer must provide specific entry point types in the add-in DLL. These entry point classes implement interfaces, either “IExternalCommand” or “IExternalApplication”, which require modifying the Revit.ini file. In this way, the add-in will run automatically for certain events or manually from the Revit External Tools menu-button. Figure 5-19 illustrates the relationship and interconnection between the Revit platform, Revit API and the Add-ins.

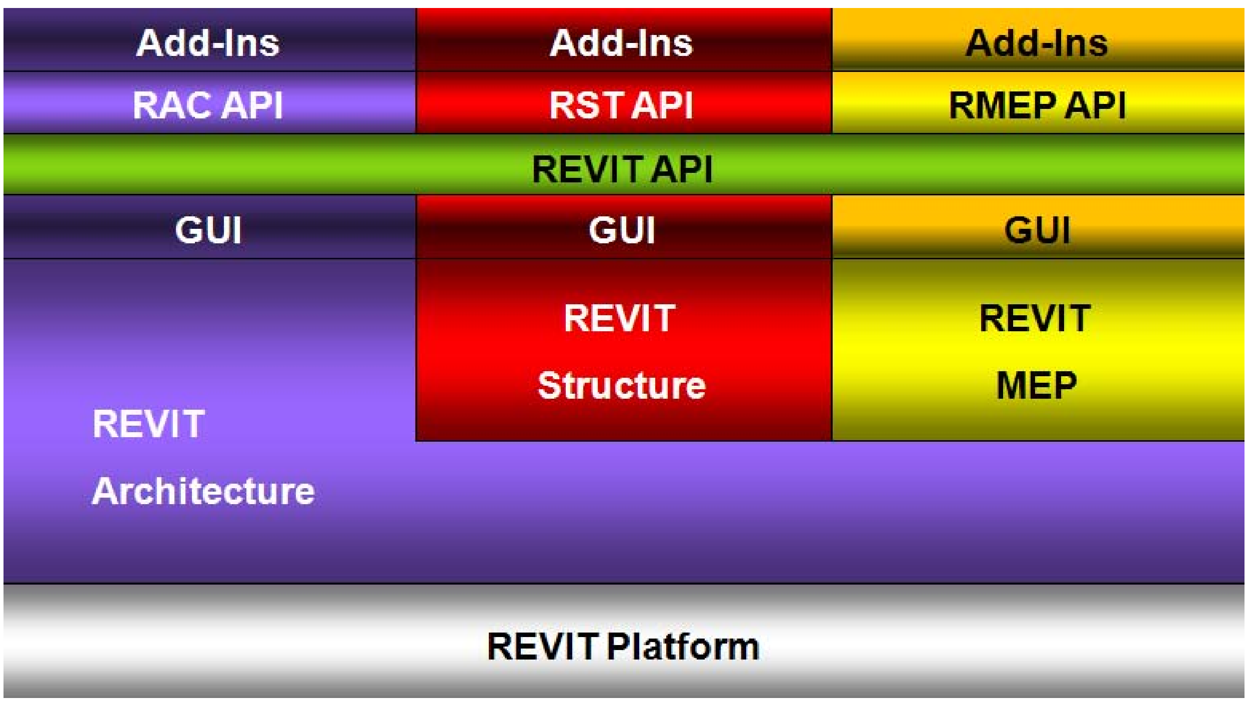


Figure 5-19. Revit, Revit API and Add-Ins. (Source: Autodesk 2009).

The add-in created by inheriting the interface IExternalCommand appears as a line item listed in the External Tools button in the Revit program. Figure 5-20 shows the steps to modify the Revit.ini file to create the desired entry point for the sample add-in “HelloWorld.”

```
[ExternalCommands]
ECCount=1 (The ECCount stands for how many external commands are already in the Revit program)
ECClassName1=HelloWorld.Class1
ECAssembly1=C:\Sample\HelloWorld\bin\Debug\HelloWorld.dll
ECName1= HelloWorld
ECDescription1=Implementation of HelloWorld within Autodesk Revit
```

Figure 5-20. “HelloWorld” add-in.

However, in order to make the sample “HelloWorld” add-in displays similar to existing Revit applications, a ribbon panel needs to be created inheriting the IExternalApplication interface and which should execute the “HelloWorld” DLL. The Revit.ini file then needs to be modified as shown in Figure 5-21.

```
[ExternalApplications]
EACount = 1 (The EACount stands for how many external applications are already in the Revit program)
EAClassName1 = AddPanel.CsAddPanel
EAAssembly1 = C:\Sample\AddPanel\AddPanel\bin\Debug\AddPanel.dll
```

Figure 5-21. Modify Revit.ini.

To provide designers with the LEED knowledge, essentially including the credit requirements and the submittal requirements, a group of LEED reference guide based normative documents are embedded into the Revit platform through the API development. These documents are PDFs (portable document format) that will be opened through the developed LEED oriented ribbon panels as external applications. Appendix C shows the process to create a “LEED Project Information” panel that hosts the “MPRs”, “Project Summary Details”, “Occupant and Usage Data”, and “Schedule and Overview Documents”, which are the four preliminary LEED Online forms to be submitted for certification review. The programming language is Visual C#, and the tool used is Microsoft Visual Studio 2008.

The created “LEED Project Information Panel” is presented in Figure 5-22. With similar methodology, all the desirable LEED knowledge can be integrated into the current Revit authoring environment to help the designers make LEED-informed design decisions. The contents of the LEED knowledge may not be limited to the generic credits or submittal information. It is more meaningful when the design company digests the USGBC LEED knowledge with their in-house knowledgebase from previous LEED project experience. The combination of the customized LEED project template, the LEED drawing sheets and the internal LEED knowledgebase constitutes quite powerful design assistance to the architects and engineers. The flexibility of the Revit API is also valuable for use in the heterogeneous environment in the AEC industry.

Module 2: Certification Management

LEED certification management is the project management tailored to deal with the certification process. Major management issues include generating documentation, collecting and managing submittals, and streamlining the application for certification. To be more specific, the documentation generation needs to take care of all the required calculations and narrative to demonstrate compliance with the attempted LEED points. The submittal collection and management needs to capture all the critical submittals that are required as supplemental evidence to the LEED point application, such as certificates, manufacturers’ cut sheets and invoices, etc. Finally, once the project team is ready to submit the application for certain LEED credits, the corresponding LEED Online template should be prepared and submitted to GBCI for review. Since normally each LEED credit will be assigned to a certain project team member, it becomes necessary to monitor the responsible party for the particular LEED credit, and track the status and potential issues raised in the project delivery.

As noted earlier in the discussion of the integration framework, there are two types of LEED credit requirements: descriptive and quantitative. For descriptive credit requirements, the documentation to demonstrate compliance often involves drawings, and narratives. For quantitative credit requirements, a certain amount of calculation is usually expectable. Bearing in mind that a calculation is always based on the existing project information, it is thus possible to take advantage of the building information model to perform most of the calculations using features/tools built in Revit. “Schedules/Quantities” is one such tool most frequently used.

A “Schedule/Quantity table is a summary of a range of relevant information for the model components in a specific category, and the table is interactive with the graphical representation of the same model component. Whenever a change is made to the model component, the table will update correspondingly, vice versa. The categories in Revit are collections of interrelated family types of building components. For instance, the category “Windows” captures all window instances in the model, regardless of the shape, size, materials and other features of the window. For each category, there are definitive parameters, which are called “fields”, to comprehensively describe the characteristics of a model component. Again taking “Windows” for example, the available fields range from the actual physical properties of the window to the installation detail, manufacturer, cost and quantity, to name a few. More importantly, if the project team wants to attach more details, Revit is flexible in allowing customized parameters to be added into existing schedules/quantities fields. Arguably, the most valuable parameter to add is the so called “Shared Parameter”.

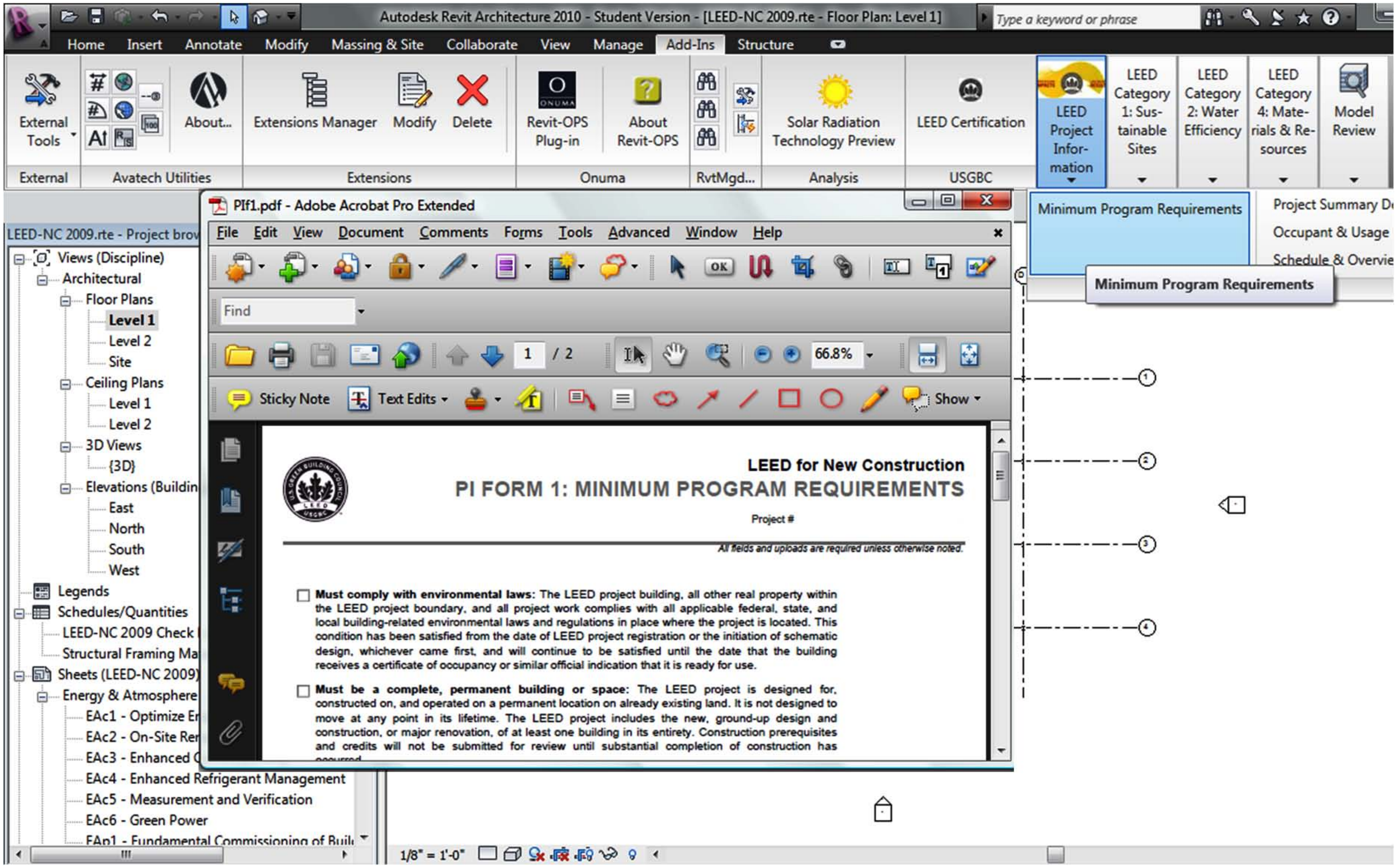


Figure 5-22. Create a LEED project information add-in through Revit API.

LEED calculation using shared parameter

In Revit, 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 to use shared parameters for LEED credits compliance have been identified in the integration framework summary. The Materials and Resources category turns out to be the best case for the application of shared parameters. Terms such as “Reused”, “Post-consumer”, “Pre-consumer”, “Regional”, “Rapidly Renewable” and “FSC” specify the materials’ LEED features, and should be defined in the LEED project template in Revit. Appendix D shows a detailed example of creating the “Post-consumer” as a shared parameter, and using it to perform the calculation for the MRc4: Recycled Content.

LEED certification management using web based application

The advantage of a web based application rests in its capacity to enable communication between project team members geographically apart. When it comes to information management, the major barrier in current practice is the inconsistent data input from different sources. This is especially true in the LEED certification process when every entity is trying to prepare the desirable documentation for the LEED credits. With an integrated and elaborately designed web application, all project members are required to upload key documents following a standardized and well controlled process. Possible errors and exceptions will be identified and tackled before damage is done to the integrity of the core project information. To be more substantial, there are two scenarios to take into account in regard to the implementation of this web-based certification management system:

- **Design credit scenario:** After the building information model is created, the project team might choose to apply for design phase submission of the applicable credits. Relevant submittal documents will be generated while the LEED Online templates are filled. However, USGBC will not award any credits until the final certification review. The project team definitely needs to backup all pertinent documents for these design credits somewhere, and expect them to be potentially updated or modified as the project progresses; and

- **Construction credit scenario:** Once the project kicks off, the general contractor and sub contractors become the major players. Typically, the general contractor is in charge of collecting, tracking and managing all pertinent project information from sub contractors in addition to their in-house documentation. At the time when a construction type credit is ready for submission, the general contractor is also obliged to check on the readiness and quality of the associated documentation.

Catering to the needs of the two scenarios, the proposed web based certification management application should possess the following features:

- **User control:** The application should define the different access levels to keep the project information secured and integrated;

- **Friendly user interface:** The application should carry an easy-understandable interface for the user to navigate through;

- **Robust functionality:** The application should allow document uploading and downloading, updating and sharing between authorized project team members;

- **Powerful database infrastructure:** The application should support automation of information acquisition and processing for the LEED certification purpose; and

- **Maintenance flexibility:** The application should allow for future expansion and enhancement to accommodate possible changes made to the LEED rating system or the BIM solution tools.

The selection of tools to create this web application requires extra prudence considering the interoperability issue in the course of data input/output. Currently, Revit supports direct data export through ODBC to Microsoft Access and Microsoft Excel. However, both Microsoft Access and Excel are not widely used as database infrastructure in web applications. A prevalent software bundle for database supported web application development is called WAMP (Windows, Apache, MySQL and PHP), where Windows is the operating system, Apache is the web server, MySQL is the database and PHP is the web scripting language. In comparison with hard coded web applications, using database support will make the maintenance much easier since no scripting will be involved but only simple updates at the data level. For a web application designed for building information modeling, this is an advantage.

Designing the web application is an intricate process. The real challenge is not from the programming requirement but the architecture of the application. The architecture makes sure that the user will follow easily understandable procedures to perform certain tasks, while the database supplies desired information to the expected outcome after running the web application. Figure 5-23 illustrates the architecture of the proposed web application.

Notice for the database part, MySQL is the direct data infrastructure of this web application. All information contained in the “Project Module” and “LEED Module” could be arranged into a MySQL database. Meanwhile, for the “BIM Module”, it is possible to export the Revit internal database through ODBC into a predefined MySQL database. Revit as a BIM authoring tool has both a graphical user interface that sits on top of a database. In essence, any instance of the model components is supported by a certain amount of data. Schedules/quantities are simply more apparent evidence of the existence of the database. Depending on the tasks that the user is performing, the “Application Service” triggers the query in MySQL to manipulate the database and generate the desired results.

To develop the MySQL database for the web application, it is necessary to sort out the relationships between different data fields. MySQL is a relational database, which

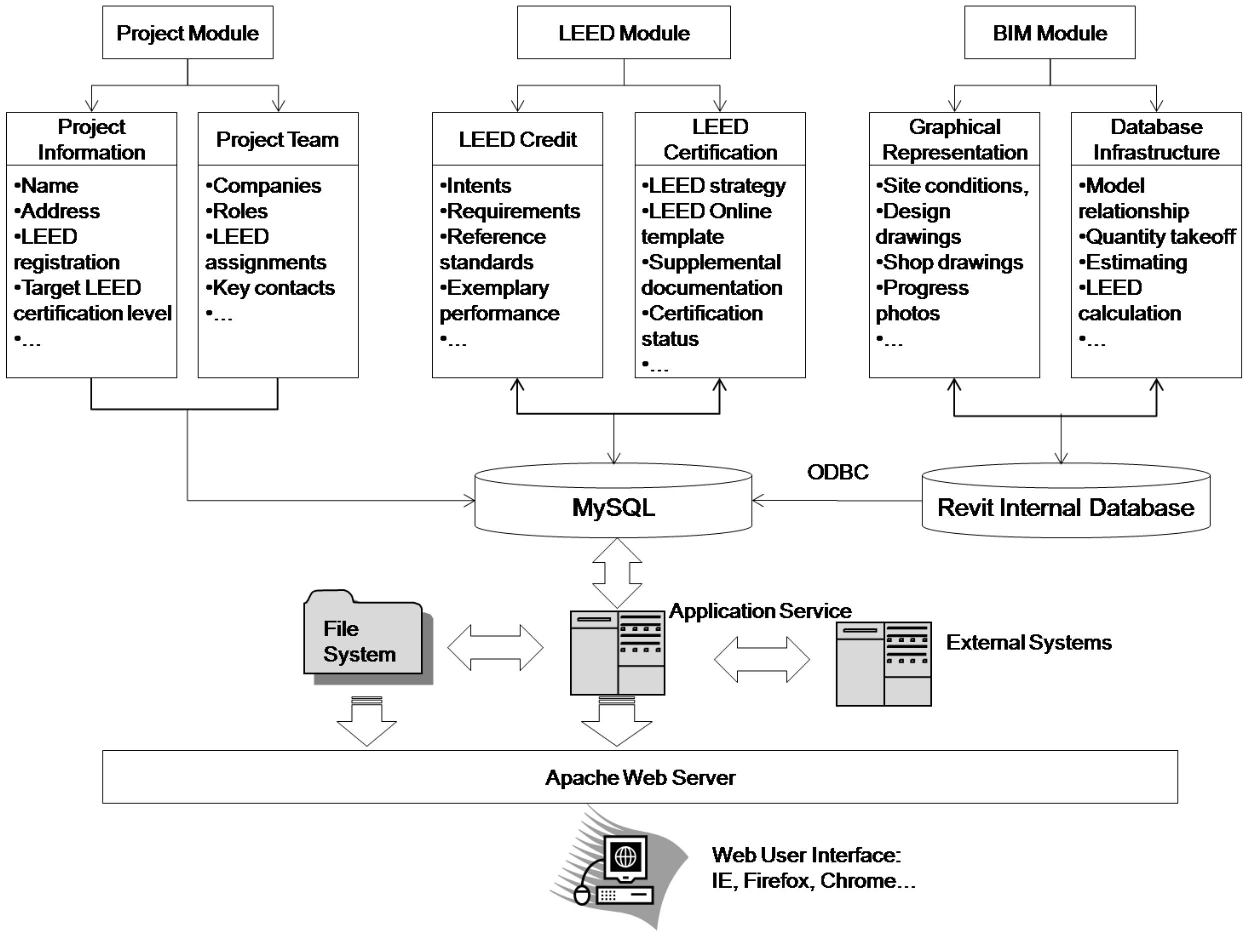


Figure 5-23. Architecture of the proposed certification management web application.

means the constituent components of it are basically interrelated tables. Each table is a collection of immediately relevant information. Tables are composed of rows and columns. In database language, each column is a “field”, and each row is a “feature”. In between the tables, the relationship is built through the use of two types of keys, the “Primary Key” and the “Foreign Key”. A primary key is used to uniquely identify each row in a table, while a foreign key is a field (or combination of fields) that points to the primary key of another table. The purpose of the foreign key is to ensure referential integrity of the data. In other words, only values that are supposed to appear in the database are permitted.

With careful research on the LEED certification process, and advice from the LEED AP interviewed, a series of tables for the “Project Module” and “LEED Module” were created and made interrelated into a MySQL database. Figure 5-24 illustrates the relationship between these tables. The goal is to extract the internal data in the building information model systematically from the Revit environment and to integrate it into the web application. This is a comprehensive data export in contrast to the single schedule/quantity or material takeoff export. It is done through the ODBC and eventually will save all the project data (a number of relational tables) into a MySQL database.

Appendix E demonstrates this process, again using the small structural framing that was created previously. The major validation task at this point is to find out through the ODBC export, whether all the information including the calculated recycled content value in the structural framing material takeoff will be available or not.

Unfortunately, the current Revit ODBC export does not fully extract the user defined data. Instead, it strictly controls the export with predefined tables and data types. In addition, the ODBC export in Revit by default adopts the metric measurement system (see marked-up area in Figure E-2), thus using the exported data to perform any kind of calculation occurs at the users’ own risk since the AEC industry in the U.S. still uses the imperial measurement system. This virtually devalues the building information model as a shared data source for the LEED project.

Consequently, with current software solutions, it is still challenging to make truly seamless information exchange happen between applications. One of the major objectives for this research is to identify such gaps in current industry software and make appropriate recommendations for future improvement. Back to the web application development, now with the MySQL database created for the “Project Module” and the “LEED Module” as shown in Figure 5-24, it is still possible to create a valuable certification management tool for the project team. The actual process will be elaborated upon in the LEED MR Use Case.

Results: LEED Materials and Resources Use Case

The use case is a simulation of implementation of the Revit – LEED application model in an actual project delivery environment. A simple renovation project is modeled in Revit as a generic building project for analysis in this use case. Considerable constraints were put in place due to the limitation of the application model as well as limitations in Revit functionality. The development process followed the steps in Figure 4-2. Discussions and evaluations were conducted along with the simulation process.

Owner’s Commitment to LEED

At this stage, the owner meets with the project team and they decide to pursue the LEED certification under the LEED-NC 2009 rating system. Then a LEED strategy is formulated specifying the certification level and the target LEED credits and points. The project is also registered with USGBC and LEED Online access is assigned to the project team. The project then kicks off, which also triggers the Revit – LEED application model.

MPRs and Prerequisites

Since the compliance with MPRs and prerequisites is mandatory, the project team should make sure that those MPRs and prerequisites are well understood. Parts of the LEED knowledge plug-ins were created to deal with this issue. In the Revit API introduction part, a “Project Information” panel has been created and codes have also been provided. The “Project Information” panel has dropdown lists of the MPR

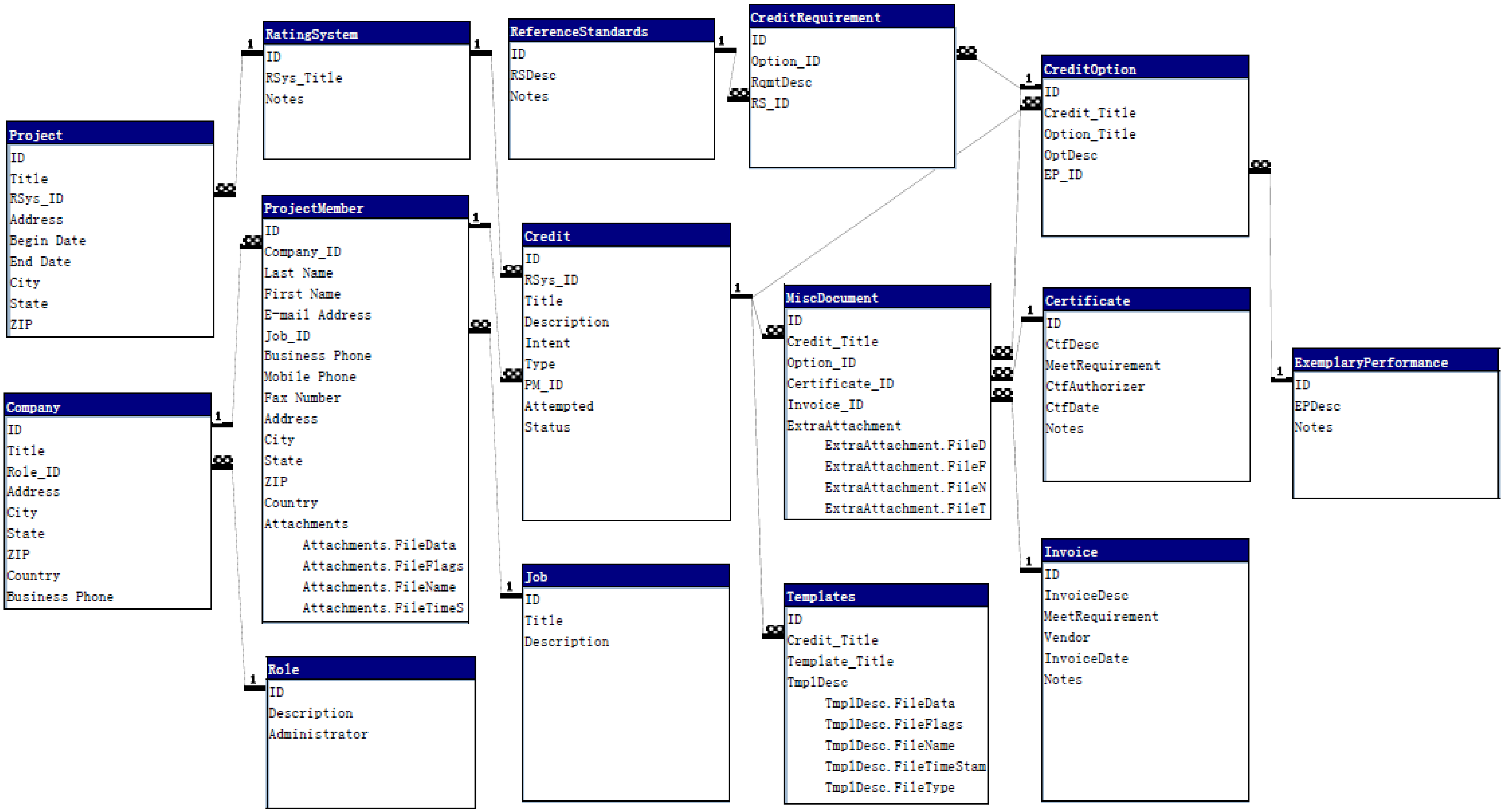


Figure 5-24. Relational tables for the certification management web application.

requirements and the associated LEED Online templates to be reviewed and filled by the project team. Although these prerequisites are mandatory, they are rudimentary requirements that are relatively easy to comply with.

Materials and Resources: Requirements vs. Functionalities

Once the MPRs are taken care of, the project team enters the stage of determining eligibility for actual credits. Through collaboration between the designers and contractors, approaches towards specific credit achievement are sorted out. In the Materials and Resources category, it takes both design and construction efforts.

The first thing the project team wants to do is to interpret the credit requirements as done in the integration framework process. Second, the project team would like to investigate BIM software they are using for the project and find out if the functionalities of the software are sufficient to provide solutions to these requirements. If it does, an action plan needs to be created; if it does not, what is the next step? The costs to pursue certain LEED points sometimes trump the technological consideration. So it is assumed that in this use case the project team wants to fully explore the MR category no matter what costs could be. The MR credits requirements vs. Revit functionality inventory is summarized in Table 5-36.

Materials and Resources: Execute Revit – LEED Application Model

The two modules for the MR category are quite straightforward. As suggested by Table 5-36, most of the requirements calculations can be done though the internal functionalities of Revit. The submittals could be prepared through the created LEED-NC 2009 project template as well. In regard to the two modules of the application model, further details of the execution process are discussed below.

Table 5-36. Prepare the Revit – LEED application model for MR credits

LEED Credit	LEED Requirements	LEED Submittals	Proposed BIM Solutions	Notes
MRp1	Recycle 5 basic materials in designated recycling area	Site plan; confirmation on materials recycled	Revit site plan with recycling area; narrative on recycled materials	
MRc1.1	Reuse building structural elements (75% or 90%) by area	Calculation of reused area (percentage)	Two-phase quantity takeoff; calculation	Phase: existing and Phase: new construction
MRc1.2	Reuse building nonstructural elements (50%) by area	Calculation of reused area (percentage)	Two-phase quantity takeoff; calculation	Phase: existing and Phase: new construction
MRc2	Divert construction waste from landfill (50% or 75%) by weight or volume	Compute percentage of total waste diverted by volume or weight ; tipping ticket or other proof	Two-phase quantity takeoff, calculation	Phase: existing and Phase: new construction
MRc3	Salvage, refurbish and reuse materials (5% or 10%) by cost	Calculation of reused materials' cost; percentage out of total material cost	Tag material using shared parameter "Reuse"; material takeoff	
MRc4	Recycled (post consumer or pre consumer) content value (10%, 20%)	Calculation of recycled contents value; percentage out of total material cost; product cut sheets indicating recycling percentage	Tag material using shared parameter "Post or pre consumer"; material takeoff	
MRc5	Use regional material (within 500 miles) more than 10% or 20% (by cost)	Calculation of regional material value; percentage out of total material cost	Tag material using shared parameter "Regional"; material takeoff	Zip codes of the project and the products may be useful
MRc6	Use rapidly renewable material more than 2.5% (by cost)	Calculation of rapidly renewable material value; percentage of total material cost	Tag material using shared parameter "RapidRenew"; material takeoff	
MRc7	Use FSC certified wood more than 50% (by cost) of total wood material cost	Calculation of FSC certified wood value; percentage of total wood material cost; FSC or COC certificate	Tag material using shared parameter "FSC"; material takeoff	

Module 1 execution: Design assistance for MR

To incorporate more environmentally friendly products into the project building information model while avoiding the depletion of natural materials, designers need to understand the strategies spelled out in the LEED rating system to encourage use of salvaged, recycled or refurbished material. Transportation of construction materials has considerable impacts on energy consumption globally. Materials that can be regenerated rapidly are much more sustainable than those that do not. Use of FSC certified wood contributes to better management of wood resources as well as fostering social-economic justice.

The LEED reference guide is the most authoritative source of assistance for the project team. It delivers the USGBC's perspective as to what is the accurate understanding of the rating system. With the reference guide built into the Revit environment, it is expected that the productivity and efficiency of LEED oriented design will be improved. With Revit API, through the "IExternalCommand" and "IExternalApplication" interfaces, a group of LEED knowledge panels for the MR category are created and attached to the Revit solution as add-ins (see Figure 5-25). The C# codes for these panels are shown in Appendix H.

A unique opportunity to assist the architects and engineers in the LEED project design will be to provide them with a comprehensive LEED material library. This library will directly interact with the material vendors' or product manufacturers' websites with level of details tailored to the LEED rating system. For instance, when the architects designate the insulation for a wall, instead of picking up a generic type they will be able to get access to a series of insulation materials with actual manufacturers' information including whether it uses rapidly renewable material, or whether it has recycled

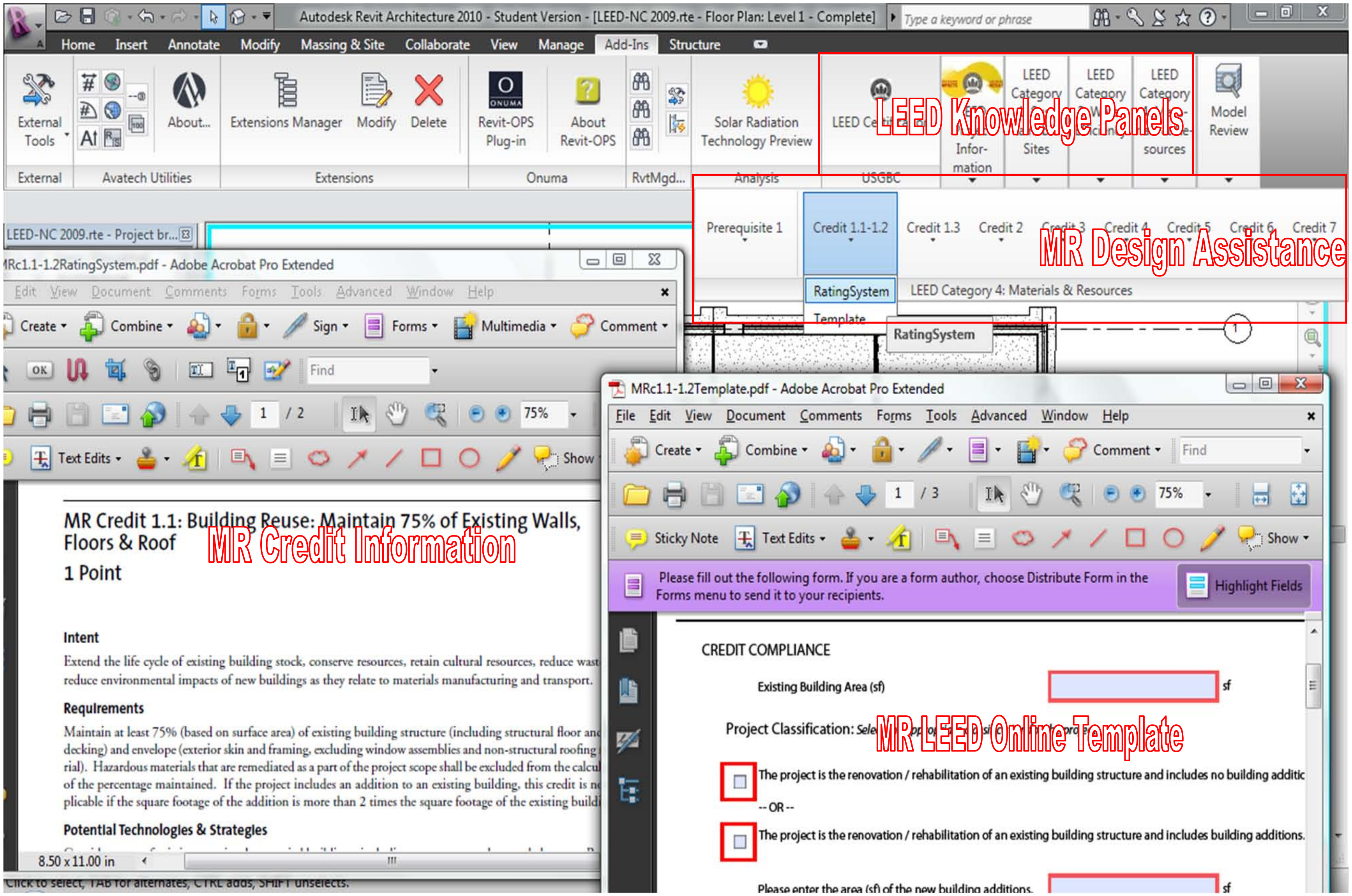


Figure 5-25. Module 1: Design assistance for MR credits.

contents, etc. Creating such a comprehensive library obviously is out of the scope of this research, but the concept is worth further investigation by software companies and material suppliers.

Module 2 execution: LEED calculation using phasing and shared parameters

Major tasks in certification management include the LEED calculation and submittal documentation management. MRp1 is simple enough to allow the use of a site plan to demonstrate the compliance (see Figure 5-26). For the rest of the MR credits, most calculations can be done inside Revit using schedules/quantities or material takeoff, which are basically spreadsheet-type tables. However, some innovations will be needed to customize these generic tables in Revit. The first innovation is to attach the “time” factor with schedule/quantity, using the “Phasing” function in Revit. The second one is the use of shared parameters that have been briefly introduced in the previous chapters.

“Phasing” is especially useful for renovation projects. It allows the designers to conveniently visualize the difference between the existing conditions and the new construction. In regard to the LEED rating system, MRc1.1, MRc1.2 and MRc2 all involve comparison between existing and new conditions. Appendix F uses a simple example to delineate using the combination of phasing and schedules/quantities to perform the required calculation for these credits. In this demonstration, only walls (exterior and interior) will be demolished to simplify the calculation. However, the methodology is applicable to more complex real world scenarios.

The rest of the MR credits, including MRc3 to MRc7, all deal with unique material properties that contribute to sustainability. These properties are not predefined in the Revit platform and thus require customization by the project team. Shared parameters turn out to be very efficient to accommodate these needs. Simply put, in order to calculate the value of materials that satisfy a certain criterion, which could vary from “reused”, “recycled”, “regional”, “rapidly renewable” to “FSC certified”, it is desirable to tag the materials in the building information model with such features.

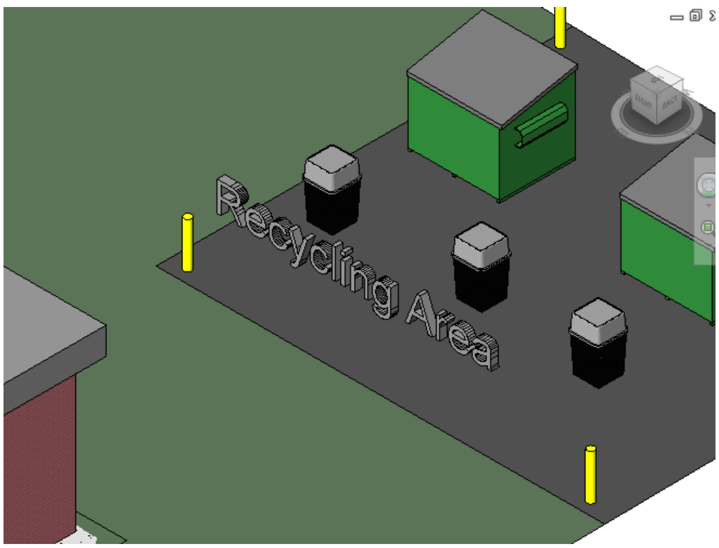


Figure 5-26. Site plan to demonstrate recycling area for compliance with MRp1.

All the desired shared parameters for the MR category have been created when conducting the demo calculation for the recycled content value of the sample structural framing project. Appendix G will go through all these shared parameters using simple demonstration.

At this point, all the required calculations for the LEED MR category have been completed. In a real LEED project the magnitude and complexity of the calculation will be at a different level, but the basic principles used in the demos will still apply. At the moment when the submittals are being collected to foster the application for these credits to GBCI, all the schedules/quantities created for calculation can be easily imported into the LEED credit sheets prepared when creating the LEED template in Revit, and become part of the submittal documentation.

During the development of these shared parameters, MRc5: Regional Materials is an interesting case. 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 resolve this problem, a distance calculator is created and embedded in Revit as part of the design assistance module. This distance calculator simply takes two parameters: the zip code of the project’s location, and the zip code of the building product. Then with a simple click of the button, the distance between the two zip codes is calculated and the result is displayed in miles. Since zip 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. Figure 5-27 illustrates the calculator application. The actual programming code for this application has largely been developed by Smith (2008) (see Appendix H).

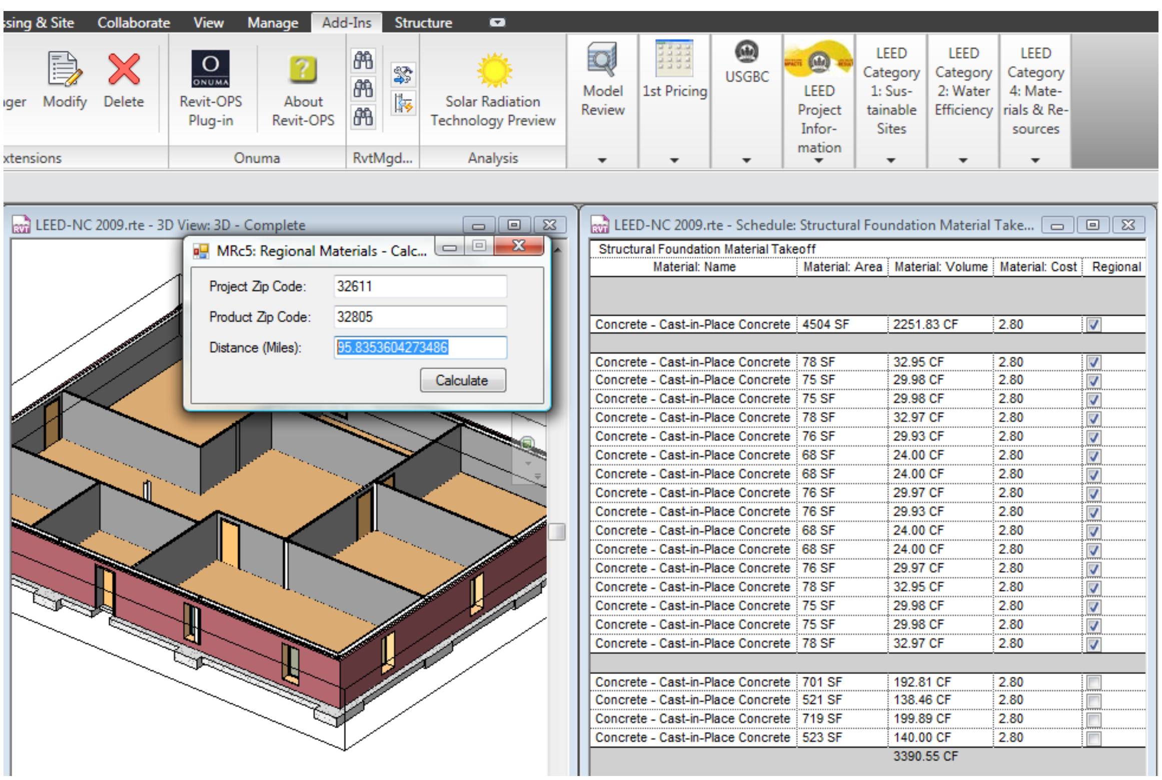
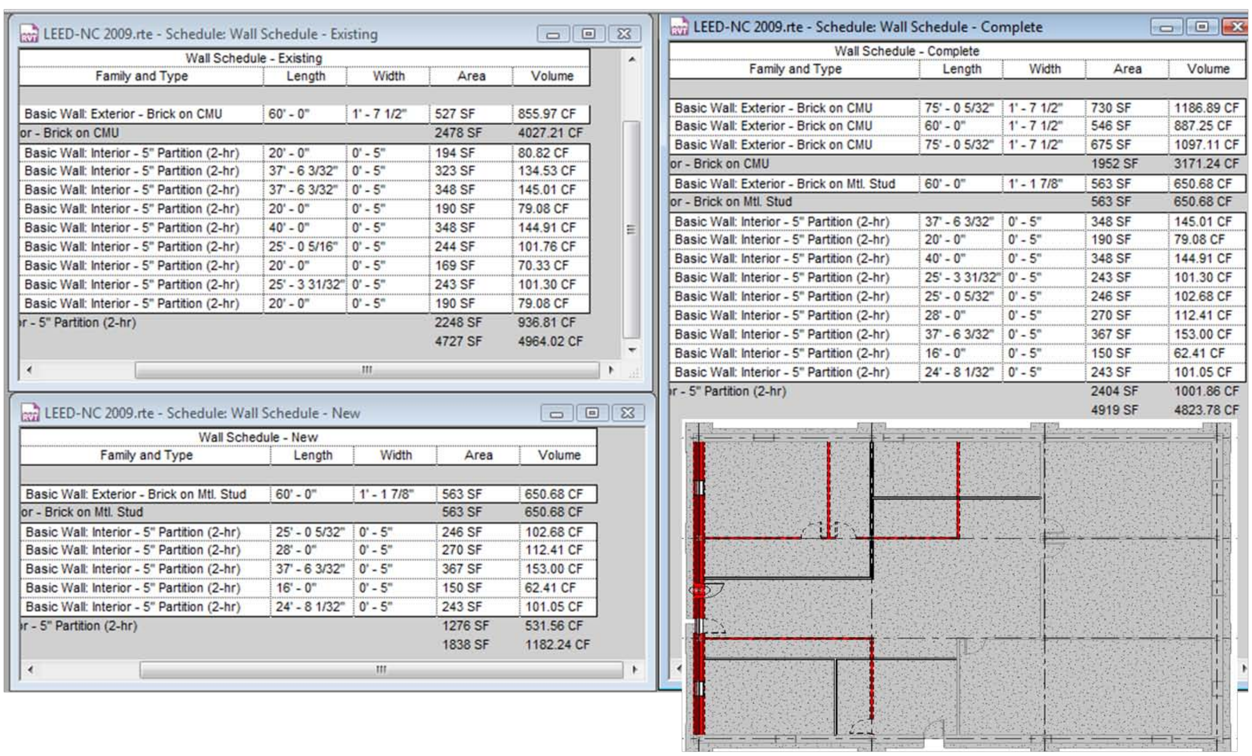


Figure 5-27. Distance calculator using zip codes for MRc5: Regional Materials.

So far all the calculation conducted for these LEED credits in the MR category is generic and model based. This brings up the question about the credibility of these calculation results. The following paragraphs use LEED MRc1.1: Building Reuse – Existing Walls, Floors and Structural Roofs as an example to further explain the application model implementation process. It also helps preliminarily validate the results generated by the application model. The simple Revit model is used again, with certain portion of the exterior wall to be demolished. By designating “Existing”, “New” and “Complete” phases to the model, three interdependent wall schedules (Figure 5-28) are created so further calculation can be conducted based on these schedules. The formula to calculate reused wall area is as follows:

```
Percentage =
      {[Exterior Wall Area (Complete)]-[Exterior Wall Area (New)]} * 100%
                     [Exterior Wall Area (Existing)]
```



LEED-NC 2009.rte - Schedule: Wall Schedule - Existing

Wall Schedule - Existing				
Family and Type	Length	Width	Area	Volume
Basic Wall: Exterior - Brick on CMU	60' - 0"	1' - 7 1/2"	527 SF	855.97 CF
or - Brick on CMU			2478 SF	4027.21 CF
Basic Wall: Interior - 5" Partition (2-hr)	20' - 0"	0' - 5"	194 SF	80.82 CF
Basic Wall: Interior - 5" Partition (2-hr)	37' - 6 3/32"	0' - 5"	323 SF	134.53 CF
Basic Wall: Interior - 5" Partition (2-hr)	37' - 6 3/32"	0' - 5"	348 SF	145.01 CF
Basic Wall: Interior - 5" Partition (2-hr)	20' - 0"	0' - 5"	190 SF	79.08 CF
Basic Wall: Interior - 5" Partition (2-hr)	40' - 0"	0' - 5"	348 SF	144.91 CF
Basic Wall: Interior - 5" Partition (2-hr)	25' - 0 5/16"	0' - 5"	244 SF	101.76 CF
Basic Wall: Interior - 5" Partition (2-hr)	20' - 0"	0' - 5"	169 SF	70.33 CF
Basic Wall: Interior - 5" Partition (2-hr)	25' - 3 31/32"	0' - 5"	243 SF	101.30 CF
Basic Wall: Interior - 5" Partition (2-hr)	20' - 0"	0' - 5"	190 SF	79.08 CF
r - 5" Partition (2-hr)			2248 SF	936.81 CF
			4727 SF	4964.02 CF

LEED-NC 2009.rte - Schedule: Wall Schedule - New

Wall Schedule - New				
Family and Type	Length	Width	Area	Volume
Basic Wall: Exterior - Brick on Mtl. Stud	60' - 0"	1' - 1 7/8"	563 SF	650.68 CF
or - Brick on Mtl. Stud			563 SF	650.68 CF
Basic Wall: Interior - 5" Partition (2-hr)	25' - 0 5/32"	0' - 5"	246 SF	102.68 CF
Basic Wall: Interior - 5" Partition (2-hr)	28' - 0"	0' - 5"	270 SF	112.41 CF
Basic Wall: Interior - 5" Partition (2-hr)	37' - 6 3/32"	0' - 5"	367 SF	153.00 CF
Basic Wall: Interior - 5" Partition (2-hr)	16' - 0"	0' - 5"	150 SF	62.41 CF
Basic Wall: Interior - 5" Partition (2-hr)	24' - 8 1/32"	0' - 5"	243 SF	101.05 CF
r - 5" Partition (2-hr)			1276 SF	531.56 CF
			1838 SF	1182.24 CF

LEED-NC 2009.rte - Schedule: Wall Schedule - Complete

Wall Schedule - Complete				
Family and Type	Length	Width	Area	Volume
Basic Wall: Exterior - Brick on CMU	75' - 0 5/32"	1' - 7 1/2"	730 SF	1186.89 CF
Basic Wall: Exterior - Brick on CMU	60' - 0"	1' - 7 1/2"	546 SF	887.25 CF
Basic Wall: Exterior - Brick on CMU	75' - 0 5/32"	1' - 7 1/2"	675 SF	1097.11 CF
or - Brick on CMU			1952 SF	3171.24 CF
Basic Wall: Exterior - Brick on Mtl. Stud	60' - 0"	1' - 1 7/8"	563 SF	650.68 CF
or - Brick on Mtl. Stud			563 SF	650.68 CF
Basic Wall: Interior - 5" Partition (2-hr)	37' - 6 3/32"	0' - 5"	348 SF	145.01 CF
Basic Wall: Interior - 5" Partition (2-hr)	20' - 0"	0' - 5"	190 SF	79.08 CF
Basic Wall: Interior - 5" Partition (2-hr)	40' - 0"	0' - 5"	348 SF	144.91 CF
Basic Wall: Interior - 5" Partition (2-hr)	25' - 3 31/32"	0' - 5"	243 SF	101.30 CF
Basic Wall: Interior - 5" Partition (2-hr)	25' - 0 5/32"	0' - 5"	246 SF	102.68 CF
Basic Wall: Interior - 5" Partition (2-hr)	28' - 0"	0' - 5"	270 SF	112.41 CF
Basic Wall: Interior - 5" Partition (2-hr)	37' - 6 3/32"	0' - 5"	367 SF	153.00 CF
Basic Wall: Interior - 5" Partition (2-hr)	16' - 0"	0' - 5"	150 SF	62.41 CF
Basic Wall: Interior - 5" Partition (2-hr)	24' - 8 1/32"	0' - 5"	243 SF	101.05 CF
r - 5" Partition (2-hr)			2404 SF	1001.86 CF
			4919 SF	4823.78 CF

Figure 5-28. Use “Phasing” to attach the “time” dimension to wall schedules.

In order to validate the results, a model based calculation (Table 5-37) is compared with the manual calculation (Table 5-38). The results from each method turn out to be consistent. But the model based calculation is much more straightforward since all the quantities are automatically generated. This can potentially prevent team members making mistakes from omitting certain building components (e.g. forget to deduct window openings from wall area) when conducting manual takeoff. Although in a real LEED project the calculations can be much more complex, the fundamental principles of these calculations are still applicable.

Table 5-37: Model based calculation for MRc1.1 – Building Reuse

Building Shell/Structure	Existing Area (SF)	Reused Area (SF)	Percentage (%) Reused
Structural Floor	4504	4504	
Exterior Wall	2478	1952	
Roof Structure	5003	5003	
Total	11985	11459	95.6%

Table 5-38: Manual calculation for MRc1.1 – Building Reuse

		Building Shell/Structure			
	QTO	Structural Floor	Exterior Wall	Roof Structure	Total
Existing	Gross Area (SF)	4500	2700	5004	
	Opening Area* (SF)	0	222	0	
	Net Area (SF)	4500	2478	5004	11982
Reused	Gross Area (SF)	4500	2100	5004	
	Opening Area* (SF)	0	165	0	
	Net Area (SF)	4500	1935	5004	11439
	Percentage (%) Reused				95.5%

With the information from these schedules/quantities and calculation tables, the project team can easily prepare the corresponding LEED Online template for MRc1.1. There also management efforts are required to make sure in actual construction process, for instance, responsible contractors should keep track of the areas of the actual demolished walls, and make sure that actually match the calculated results obtained from the Revit model. Figure 5-29 describes the suggested procedures for complete application model implementation process.

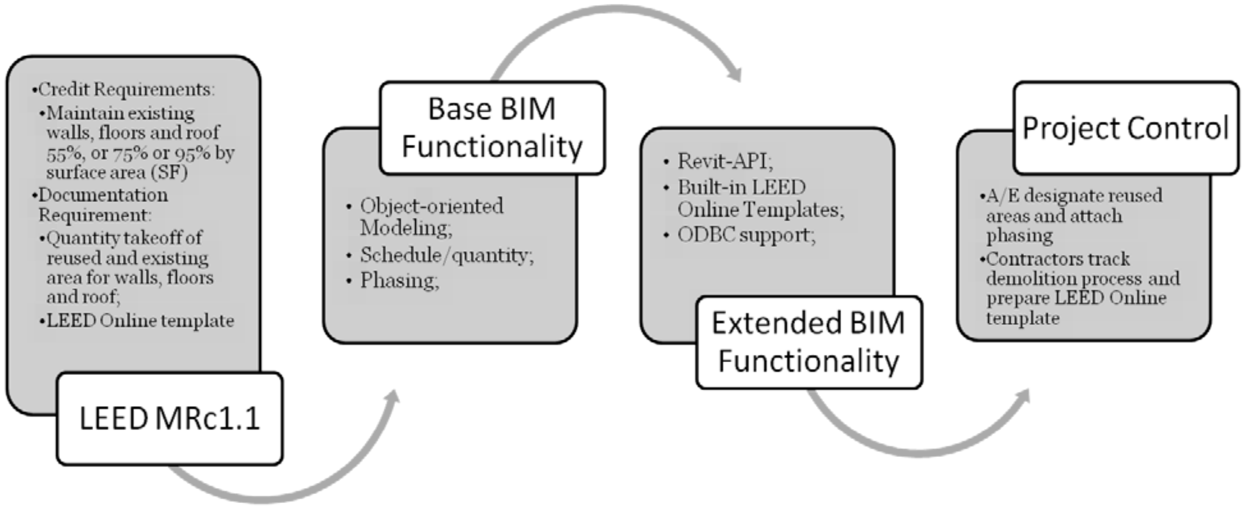


Figure 5-29. Suggested application model implementation procedures.

Module 2 execution: LEED certification management using web application

When the Revit – LEED application model proceeds to this step, all the MR credit requirements should have been fulfilled. Along with the LEED project delivery process, a large amount of project documents are to be generated and managed for submission to GBCI for review. The LEED Online templates and the supplemental documents for each MR credit obviously are the most critical ones. The web application is a step-by-step guidance and data server for the LEED project team to manage the certification process. With different access levels to the web application, team members could upload, download, update and submit relevant documents for the LEED credits assigned to them. As previously described, there are two modules in the web application architecture: Project Module and LEED Module. Accordingly, the execution of the web application has two stages:

- **Stage 1:** The user will login with assigned username and password, and fill in general project and personal information relevant to the LEED project. Then a list of questions will be asked to help the user review some critical issues about the credits assigned to them, starting from the credit information such as credit intent, requirements, reference standards, exemplary performance, to required submittal requirements. This is to verify that the users fully understands their obligation especially the information expected from them to support the corresponding LEED credit application; and
- **Stage 2:** The web application provides functionalities catering to the ordinary file systems that support upload, store, download and update of LEED Online templates and other pertinent submittals.

The web application operates on top of the MySQL database, and is powered by the Apache Web server, using PHP for server-side scripting. It is intelligent since depending on the inputs at a previous step, the user will be directed to a different ensuing step, which is controlled by the web designer with direct data population from the MySQL database underneath the browser interface. Meanwhile, with the embedded features in web browsers, project members can easily perform printing, sending emails or other everyday communication activities. Figure 5-30 presents the preliminary user interface of this LEED certification management web application. It is however not the major concern of this research to fully develop this application considering that the only part left is the programming.

Once the credits are ready and submitted to GBCI for review, the work platform will transfer to the LEED Online website. However, this web application can still contribute to the LEED certification process by archiving the documents and potentially provide back-up evidence for further details if required by the GBCI reviewers. At this point, the use case for LEED Materials & Resources category is officially completed.

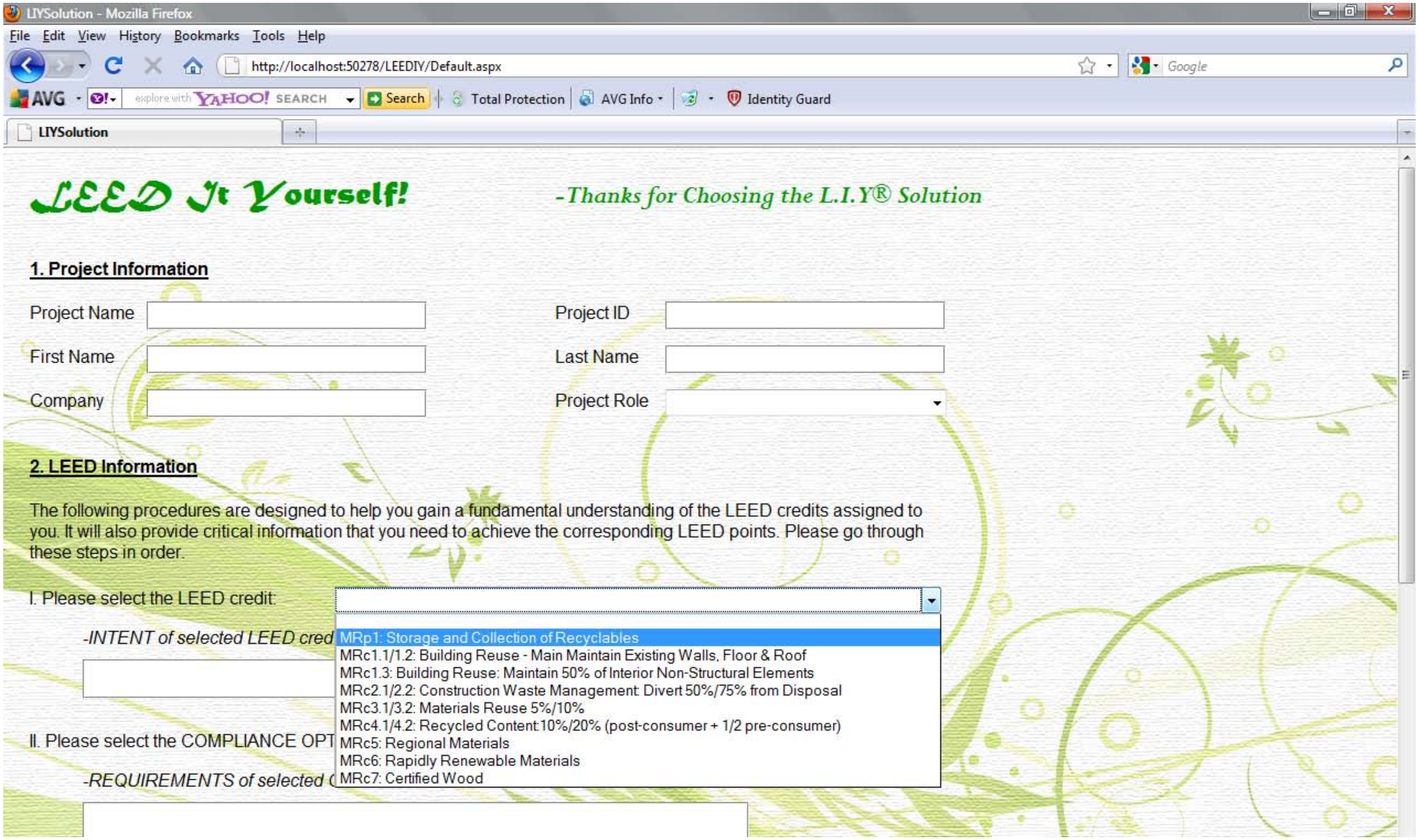


Figure 5-30. User interface of proposed LEED certification management web application.

Discussion: Code Checking for LEED Certification

The concept of code checking has been briefly introduced in the literature review. The International Code Council (ICC) is leading the global efforts to promote automated building code checking by model checking software such as CORENET e-plan checking system, Solibri Model Checker and AEC3's BIMService.

In order to tackle the heterogeneous environment in the AEC industry, ICC has been dedicated to IFC model based code checking. The major components in this IFC-centric process and the fundamental workflow are illustrated in Figure 5-30. Suppose that the "code" to be checked is LEED or other green building rating system, this workflow then becomes a "sustainability" checking system.

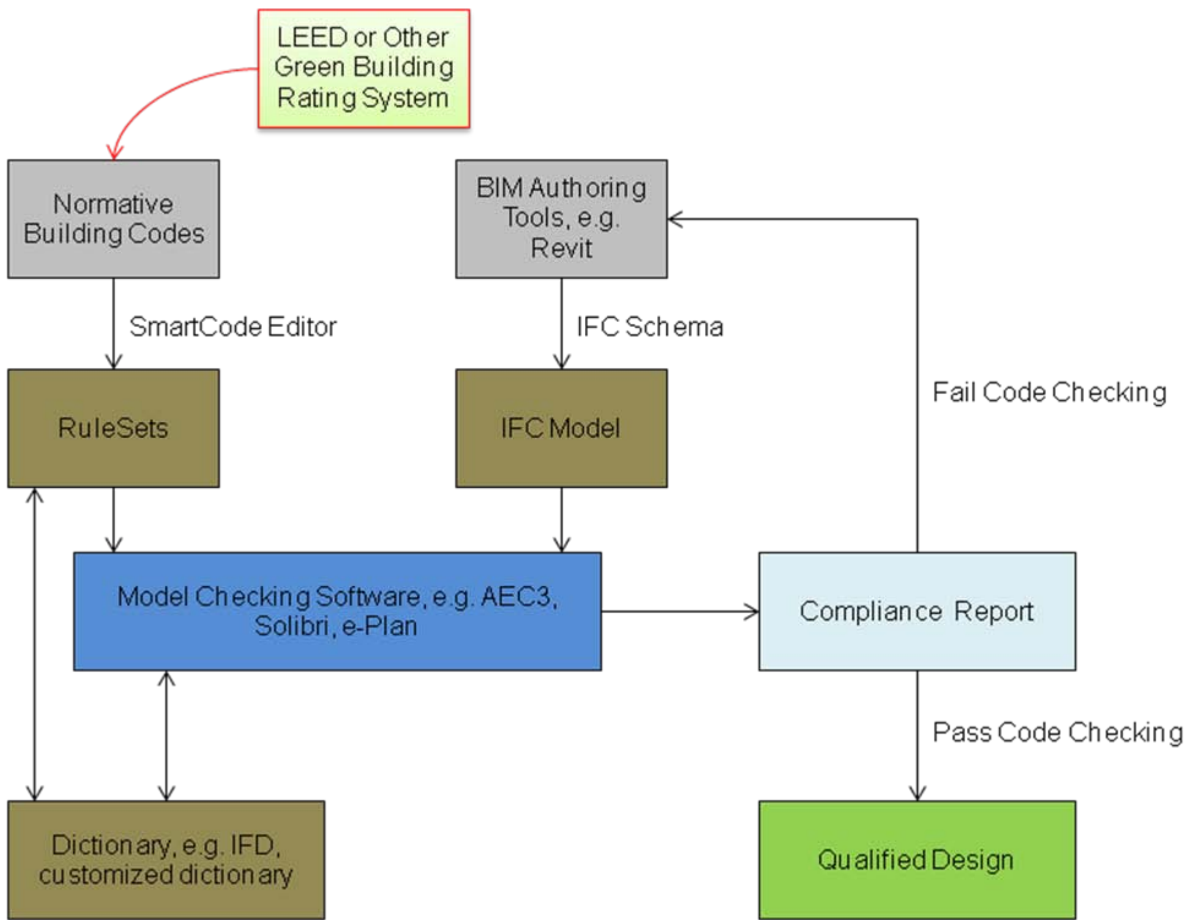


Figure 5-31. Components and workflow in an IFC based code checking.

However, to realize the automated LEED-checking process for the purpose of achieving LEED certification, this code checking approach is still problematic due to the following constraints:

- First and foremost, the LEED rating system is not yet a standard or a code, its legitimacy as the scientific guidance to green building is still to be justified;
- Current IFC schema is a very general framework while every single building project is unique. This discrepancy causes inevitable loss of project information during the conversion from BIM authoring format (e.g. Revit format) to the IFC model that will be checked by the code checking engine;
- The dictionary in the code checking process interprets the important ontology and semantic information between the RuleSets and the IFC model. However, current dictionary framework such as the International Framework for Dictionaries (IFD) is far from complete. This discrepancy causes omissions in the code checking process against certain RuleSets, which might be extremely critical to the quality control of the IFC model being checked;
- The format of the compliance report now is very limited and not user-friendly. For LEED projects, it will be a huge barrier if the project team could not interpret the compliance report and use the result to guide the actual project delivery. There will be little value to the LEED project team to go through this relatively complex process yet get nothing valuable out of it.

Despite of the above constraints, governmental agencies and the AEC industry have been dedicated to prescribing buildings codes specially conceived for green buildings. The research on the code-checking approach to achieve LEED certification is ongoing and some significant changes have to take place to make this approach more feasible:

- The IFC and IFD framework need to keep evolving to accommodate the special need for sustainability, in terms of ontology and semantics. The green building movement has been transforming the industry in an unprecedented manner, new concepts and knowledge will take some time for the industry to completely absorb and digest into standard practice. Enriching the vocabulary of sustainability and green building in the IFC/IFD framework is a must;
- New building codes catering to green building regulations need to be more performance based. The automated code checking process relies heavily on the

appropriately interpreted RuleSets, which tend to be prescriptive and whose quality is directly determined by the green building code itself; and

- The user interface of the code checking software should be improved to account for the needs of ordinary industry players whose IT knowledge or infrastructure is limited. A more user-friendly software application is important to promote the adoption of building information and other new construction IT products in the AEC industry.

CHAPTER 6
CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS

Conclusions

This research acknowledged BIM and green building as the two major trends in the AEC industry. Based on that premise it proposed a new strategy for the AEC professionals to achieve popular green building certification such as LEED through the integration of BIM and green building rating systems. In response to the research Objective I, the first step taken was to conduct a feasibility analysis survey to investigate the two most fundamental questions in the BIM and LEED integration: 1) What LEED requires; and 2) What BIM can provide. Following that, to fulfill research Objective II, a comprehensive integration framework was established to prepare the theoretical foundation for pragmatic solutions to this integration. The integration framework matched up the LEED credit/certification requirements with the functionality inventory in popular BIM software solutions such as Revit from Autodesk. During the match-up 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. Then the functionality inventory of BIM software was screened to provide solutions to these data requests. Gaps were identified when there was no immediate functionality available in current BIM software to achieve compliance with certain LEED credits.

In response to research Objective III and IV, the Revit – LEED application model was created on top of the integration framework to deal with practical problems at the credit level in actual LEED projects. The Revit – LEED application model consisted of two modules: “Design Assistance” and “Certification Management” to accommodate the needs along with the LEED project delivery and certification process. The “Design Assistance” module took advantage of the Revit API to provide the designers with off-the-shelf LEED knowledge inside the Revit environment to ensure accomplishment of the LEED oriented design. The “Certification Management” module was a web based application built upon the Apache/MySQL/PHP platform. It focused on the compliance with LEED credits as well as the management of documentation and submittals for certification purpose.

Finally, to fulfill research Objective V, the LEED Materials and Resources use case was created to preliminarily validate the Revit – LEED application model by simulating the real LEED certification process. Technical details in implementing the Revit – LEED application model were delineated using a number of demos. Project teams should be able to take advantage of the results of the use case in real LEED project, apparently at a whole different level of complexity and magnitude.

Overall, the research demonstrated that BIM and LEED integration was feasible with considerable constraints. The BIM – LEED application model on the other hand, was quite sufficient for the LEED MR use case. The perceived constraints were majorly attributed to functionality limits of the BIM software selected, for instance, the absence of GIS linkage, lack of material library that captures industrial product data, and the immature support for interoperability at database level. There were also constraints due to the intrinsic features of the LEED rating system that are simply not applicable to BIM integration.

Limitations

The biggest limitation of this research is that the proposed integration framework and application model have never been fully validated in real LEED projects. This is also the next immediate step needed to make the results of this research truly helpful to AEC professionals. 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, the 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 technology.

In the course of creating the integration framework, it was noticed that there were still considerable gaps between the LEED credit/certification requirements and available functionalities of current BIM software solutions. The advancement of BIM technology needs to keep the momentum and make it possible to deal with more stringent modeling requirements oriented towards sustainability. Conversely, the LEED rating system itself is problematic to some degree. A major problem would emerge when the project team decided to game the system, meaning that they made no significant improvement of building performance but somehow managed to achieve the LEED certification. Some of the existing LEED credits were quite trivial to buildings' green performance (e.g. bicycle racks), while quite a few critical sustainability indicators failed to be incorporated into the LEED system (e.g. carbon footprint). To promote the AEC industry's transition to green with BIM, a truly performance-based green building standard is desirable. The advent of the green building codes discussed previously is an encouraging sign.

Interoperability is another bottleneck that limits the development of the integration framework. It will also eventually determine the integration level between BIM and sustainability considering that information exchange is the bottom line in project management. A huge setback in current interoperability frameworks such as IFC/IFD is the lack of ontology and semantics to describe the vocabulary of sustainability in a format that can be read and understood by computers. Meanwhile, interoperability support from popular BIM software at the database level is still underdeveloped. 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.

Recommendations for Future Research

Buildings and building systems are complex, interactive and dynamic, especially when perceived as the interface between nature and the human society. Technologies can help configure, control and improve building performance to the level that how much buildings are understood by human beings. Sustainability adds extra dimensions to such understanding. The technologies that accommodate the requirements prescribed by the sustainability principles are advancing all the time, but not at the same pace. “Energy” is arguably the most well researched area, while indoor environmental quality is still primitively understood by professionals. New issues such as carbon emissions may be also of interest to BIM practitioners. To achieve well balanced building performance, BIM development needs reinforced efforts at the full spectrum of issues in building design and construction. Desirable researches may include more in-depth analysis of implementing BIM in building processes such as commissioning and facility management, or look into specialized BIM technology development tailored to certain building types such as health care or educational facilities.

Meanwhile, integrating information technology such as BIM with sustainability principles should be careful and not to eschew from the fundamental goals of promoting the productivity and improving profitability in the AEC industry. Companies, especially small and medium sized, are often reluctant to changes in fear of increased risk and financial uncertainties. The cost implication of integrating new technology with the companies' business strategy becomes a critical research topic to support sound decision-making. Stakeholders of the companies may want to know how big the investment is going to be, including software, hardware and training; what return-on-investment (ROI) rate they can expect; what financial risks and other uncertainties are involved, etc. Once companies are committed to adopt the integrated BIM-Sustainability strategy, they need both technical support and more importantly, the managerial support. BIM and sustainability are features of a new business paradigm, so will current project delivery methods still be effective? How will the new integrated project delivery (IPD) help in the companies' adaptation to the new business paradigm? What fundamental changes should be made to the companies' existing structuring, operating, staffing and profiting? Those are also imperative questions that need to be investigated.

APPENDIX A
FEASIBILITY SURVEY OF BIM FOR LEED CERTIFICATION

This survey intends to investigate the possibility of using current BIM authoring tools to facilitate the LEED-NC certification (LEED-NC 2009) process, with emphasis on the data extraction and information exchange during the project delivery. As a proof of concept, the result of this survey will be incorporated into the author's doctoral dissertation on BIM-for-Sustainability in more depth.

PART 1: General Questions

1. Please describe your/your company's role in a construction project:
   a. Owner
   b. A/E
   c. General Contractor
   d. Subcontractor
   e. Other (Please specify____)

2. According to National BIM Standard (NBIMS), BIM is "the virtual representation of the physical and functional characteristics of a facility from inception onward. As such, it serves as a shared information repository for collaboration throughout a facility's lifecycle". Under this definition, please describe your/your company's experience with BIM:
   a. Understand the concept only
   b. Have purchased BIM authoring tools and started employee training
   c. Have participated in projects using BIM as reference only
   d. Have participated in projects partially adopting BIM
   e. Have participated in projects fully adopting BIM (Plan, Design, Construction and O&M)
   f. Other (Please specify____)

3. Please specify the BIM authoring tool(s) used in your company (select all that apply):
   a. Revit Suite (Architecture, Structure and MEP)
   b. Bentley System
   c. ArchiCAD
   d. Vico Software
   e. Vectorworks
   f. Other (Please specify____)

4. Please describe your/your company's experience with LEED for New Construction and Major Renovation (LEED-NC):
   a. Understand the concept only
   b. Have in-house LEED-APs but no actual LEED-NC project experience
   c. Have participated in projects that pursued LEED-NC certification but failed
   d. Have participated in projects that pursued LEED-NC certification and succeeded
   e. Other (Please specify____)

PART 2: BIM for LEED-2009 Certification

Section 1: Perception Research

The following questions enquire about your personal perceptions regarding using BIM authoring tools to facilitate the LEED-NC certification process based on your understanding or actual work experience. Currently in the market, LEED-NC Version 2.2 (LEED-NCv2.2) is the major certification system, but there are lots of concerns regarding the new LEED v3 system.

Due to the facts that most under construction and completed LEED certified projects use LEED-NC v2.2, please answer the following questions based on LEED-NC v2.2.

Perceptions	Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
Likert Scale	1	2	3	4	5	6	7
1. Current BIM authoring tools have been sufficiently designed to meet LEED-NC v2.2 requirements							
2. Your company has fully integrated BIM authoring tools in LEED-NC v2.2 project delivery							
3. Current BIM authoring tools are effective in preconstruction stage of LEED-NC v2.2 projects							
4. Current BIM authoring tools are effective in construction stage of LEED-NC v2.2 projects							
5. Current BIM authoring tools could help formulate strategies targeting LEED credits/points							
6. Current BIM authoring tools could facilitate generation and dissemination of design and contract documentation							
7. Current BIM authoring tools could facilitate communication and information exchange between project members in LEED project							
8. Current BIM authoring tools could facilitate documentation generation and submission as required by LEED-NC v2.2 certification process, e.g. LEED online							
9. Current BIM authoring tools could help reduce the upfront cost of pursuing LEED-NC v2.2 certification							
10. Current BIM authoring tools could increase the overall chances of achieving LEED-NC v2.2 certification							

Section 2: BIM for LEED-NC 2009 Applicability Research

The following questions will ask you to project the "applicability" of implementing BIM authoring tools to streamline the LEED®-NC 2009 certification process based on your understanding of this new system. By April 27th 2009, the USGBC has finished updating their service to accommodate the new LEED v3 (the whole package including all the 2009 version of LEED rating systems, see http://www.usgbc.org/DisplayPage.aspx?CMSPageID=1970 for more details), and the most updated LEED-NC 2009 rating system can be obtained from USGBC following the link: http://www.usgbc.org/ShowFile.aspx?DocumentID=5546.

The following questions are strictly formulated according to the 7 categories in the LEED-NC 2009 scoring system. One criterion you may consider using to determine the capacity of BIM authoring tools could be “how those authoring tools will help in the LEED Online templates preparation”, in that LEED Online has been the major interface for communication between the project team and USGBC.

LEED-NC 2009 Categories and Credits	Applicability of BIM Authoring Tools					
	Not applicable	Hardly Applicable	Somewhat Applicable	Moderately Applicable	Applicable	Highly Applicable
	0	1	2	3	4	5
Category 1: Sustainable Sites						
SSp1: Construction Activity Pollution Prevention						
SSc1: Site Selection						
SSc2: Development Density and Community Connectivity						
SSc3: Brownfield Development						
SSc4: Alternative Transportation						
SSc5: Site Development						
SSc6: Stormwater Design						
SSc7: Heat Island Effect						
SSc8: Light Pollution Reduction						
Category 2: Water Efficiency						
WEp1: Water Use Reduction						
WEc1: Water Efficient Landscaping						
WEc2: Innovative Wastewater Technologies						
WEc3: Water Use Reduction						
Category 3: Energy and Atmosphere						
EAp1: Fundamental Commissioning of Building Energy Systems						
EAp2: Minimum Energy Performance						
EAp3: Fundamental Refrigerant Management						
EAc1: Optimize Energy Performance						
EAc2: On-site Renewable Energy						
EAc3: Enhanced Commissioning						
EAc4: Enhanced Refrigerant Management						
EAc5: Measurement and Verification						
EAc6: Green Power						
Category 4: Materials and Resources						
MRp1: Storage and Collection of Recyclables						
MRc1: Building Reuse						
MRc2: Construction Waste Management						
MRc3: Material Reuse						
MRc4: Recycled Content						
MRc5: Regional Materials						
MRc6: Rapidly Renewable Materials						

MRc7: Certified Wood	
Category 5: Indoor Environmental Quality	
IEQp1: Minimum IAQ Performance	
IEQp2: Environmental Tobacco Smoke Control	
IEQc1: Outdoor Air Delivery Monitoring	
IEQc2: Increased Ventilation	
IEQc3: Construction IAQ Management Plan	
IEQc4: Low-Emitting Materials	
IEQc5: Indoor Chemical and Pollutant Source Control	
IEQc6: Controllability of Systems	
IEQc7: Thermal Comfort	
IEQc8: Daylight and Views	
Category 6: Innovation and Design Process	
IDc1: Innovation in Design	
IDc2: LEED® Accredited Professional	
Category 7: Regional Priority	
RPc1: Regional Priority	

PART 3: Comments and Suggestions

Thanks for your time! Please feel free to make any further comments or suggestions below that you think will be beneficial to investigate the potential of using BIM authoring tools to facilitate the LEED®-NC certification process and project delivery:

____

____

____

____

If you have any other enquiries or any relevant research that you would like to discuss with the author, please feel free to contact:

Wei Wu
PhD Candidate, LEED-AP
Rinker 341, Powell Center for Construction and Environment
Rinker School of Building Construction
University of Florida
Email: vjwwlc@gmail.com
Cell: +1 352 328 7299

APPENDIX B
DEMO: LEED TEMPLATE IN REVIT

1. Go to and select "New" project;
2. Select "none" for Template file and select "Create" a new "Project template" (Figure B-1), when prompted, select using "Imperial" measurement system;

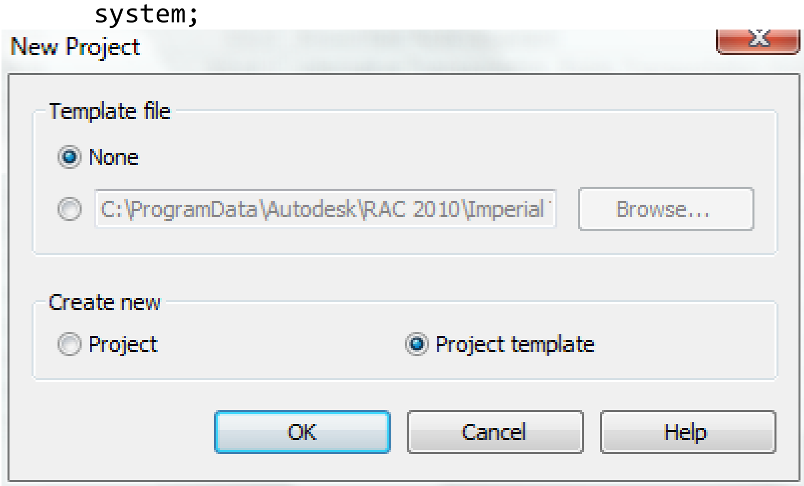


Figure B-1. Create new project template in Revit.

3. Go to "View", and click on the "Schedules" dropdown list, select "Drawing List";
4. In the "Drawing List Properties" dialogue box, add "Sheet Number", "Sheet Name" to the "Scheduled fields";
5. Click "Add Parameter" to create new "Project Parameter", grouping the newly created "Project Parameter" under "Green Building Properties". The "Name", "Discipline" and "Types" of the parameters should depend on the actual needs (Figure B-2);

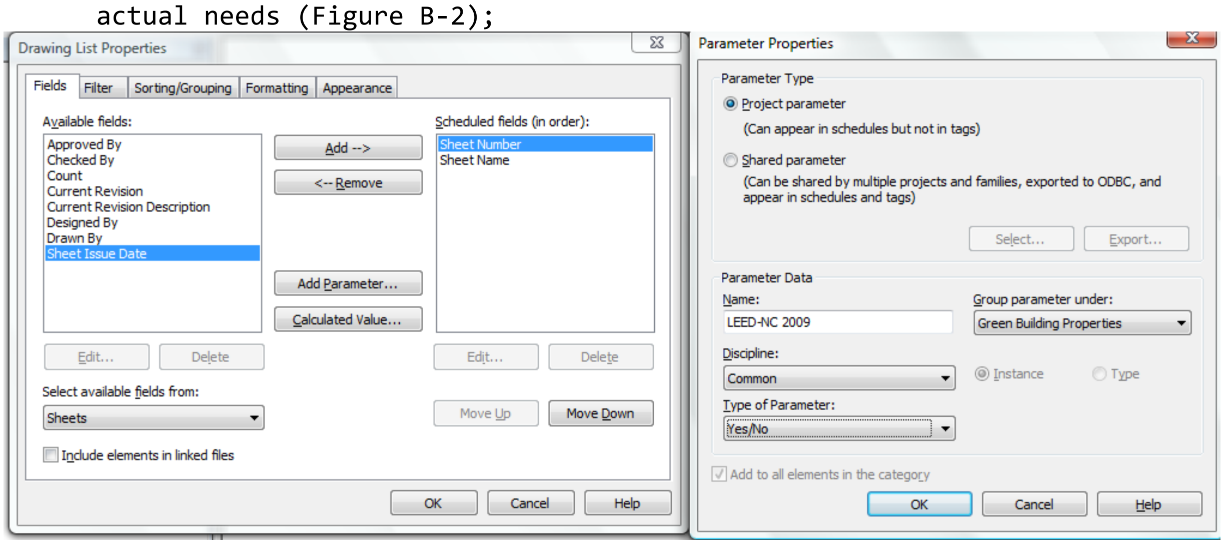


Figure B-2. Add new "Green Building Property" into template.

6. Create new “LEED-NC 2009” (Common, Yes/No), “LEED Category” (Common, Text), “Points Achievable” (Common, Integer) and “Points Attempted” (Common, Integer) project parameters into the “Scheduled fields” and finish creating the “Drawing List”. Of course, some “Sorting/Grouping” and “Formatting” could be done to make the “Drawing List” more organized;
7. Before actual drawing sheets are created, the “Drawing List” schedule should be empty. So next, go to “Sheets” in the “Project Browser”, right click and select “New Sheet”. Select any “Titleblock” with the suitable size, and create the new drawing sheet;
8. Right click the newly created drawing sheet, and select “Properties”. Locate the “Green Building Properties” to view all the customized “Project Parameters” created in previous steps.
9. Input the appropriate information into these “Green Building Properties”, and finalize the other details of the drawing sheet such as the “Sheet Number” and “Sheet Name”, and then finish editing (Figure B-3);

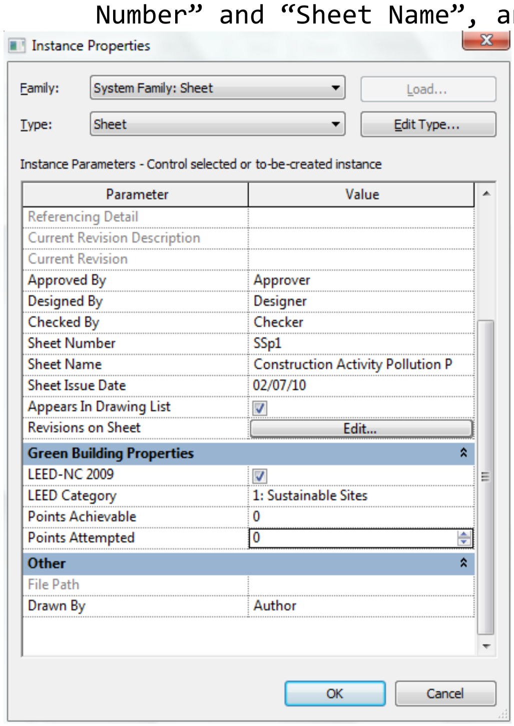


Figure B-3. Create a LEED-NC 2009 drawing sheet.

10. Now take a look at the “Drawing List” schedule again, the newly added drawing sheet with all the fields filled should appear (Figure B-4);

LEED-NC 2009					
LEED Category	Sheet Number	Sheet Name	LEED-NC 2009	Points Achievable	Points Attempted
1: Sustainable Sites					
1: Sustainable Sites	SSp1	Construction Activity Pollution Prevention	☑	0	0

Figure B-4. Populate the LEED-NC 2009 drawing list schedule.

11. Repeat Step 7-9 to add all the desired drawing sheets and the customized LEED-NC 2009 template will be created.

APPENDIX C
SAMPLE CODES: LEED KNOWLEDGE PANEL

Create the application inheriting IExternalCommand:

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using Autodesk.Revit;
using System.Windows.Forms;
using System.Diagnostics;
using System.IO;

namespace LeedCertification
{
    class piF1:IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\PI\PIf1.pdf");

            return IExternalCommand.Result.Succeeded;
        }
    }

    class piF2 : IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\PI\PIf2.pdf");

            return IExternalCommand.Result.Succeeded;
        }
    }

    class piF3 : IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\PI\PIf3.pdf");

            return IExternalCommand.Result.Succeeded;
        }
    }
```

```
    class piF4 : IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\PI\PIf4.pdf");

            return IExternalCommand.Result.Succeeded;
        }
    }
}
```

Create the panel inheriting IExternalApplication:

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using Autodesk.Revit;
using System.Windows.Media.Imaging;

namespace AddPanel
{
    public class CsAddpanel:IExternalApplication
    {
        public IExternalApplication.Result OnStartup(ControlledApplication
application)
        {
            string assembly =
@"C:\REVITLEED\LeedCertification\LeedCertification\bin\Debug\LeedCertification.dl
l";

            RibbonPanel piPanel = application.CreateRibbonPanel("LEED Project
Information");
            PushButton piF1 = piPanel.AddPushButton("Minimum Program
Requirements", "Minimum Program Requirements", assembly,
"LeedCertification.piF1");
            piF1.Image = new BitmapImage(new
Uri(@"C:\REVITLEED\Images\MPR.bmp"));

            piPanel.AddSeparator();

            PushButtonData piF2 = new PushButtonData("Project Summary Details",
"Project Summary Details", assembly, "LeedCertification.piF2");
            PushButtonData piF3 = new PushButtonData("Occupant & Usage Data",
"Occupant & Usage Data", assembly, "LeedCertification.piF3");
            PushButtonData piF4 = new PushButtonData("Schedule & Overview
Documents", "Schedule & Overview Documents", assembly, "LeedCertification.piF4");

            piPanel.AddStackedButtons(piF2, piF3, piF4);
```

```
            return IExternalApplication.Result.Succeeded;
        }

        public IExternalApplication.Result OnShutdown(ControlledApplication
application)
        {
            return IExternalApplication.Result.Succeeded;
        }
    }
}
```

Modify the Revit.ini file:

```
[ExternalApplications]
EACount=8
EAClassName8=AddPanel.CsAddpanel
EAAssembly8=C:\REVITLEED\AddPanel\AddPanel\bin\Debug\AddPanel.dll
```

APPENDIX D
DEMO: SHARED PARAMETERS

1. Open a new Revit project, go to “Manage”, click on “Shared Parameters”, create a new text file to store the new shared parameters to be created, and save (Figure D-1);

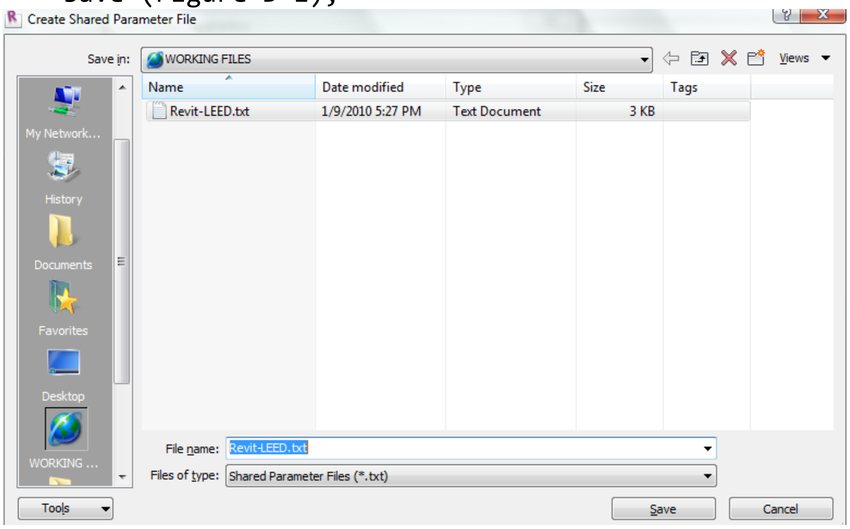


Figure D-1. Create a new shared parameter file Revit-LEED.txt.

2. In the “Edit Shared Parameters” dialogue box, add a new “Group” of “MR” for the shared parameters to be created for the MR category;
3. Under the new MR Group, add new shared parameters including “PostConsumer” and “PreConsumer”, and define the discipline as “Common”, the data type as “Yes/No”. Other shared parameters for the MR category may include “Reuse”, “Regional”, “RapidRenew” and “FSC” (Figure D-2);

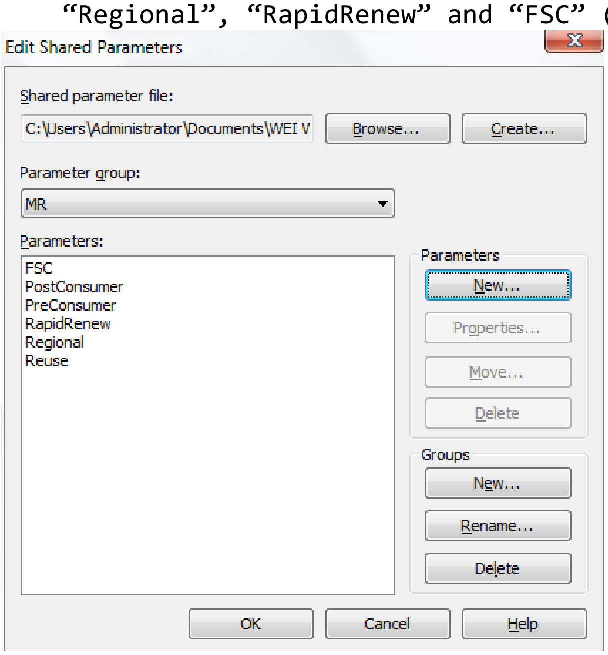


Figure D-2. Add desired shared parameters and groups.

4. Create a small structural framing using wide flange beams (W12x16). In order to normalize the weight for W12x16, open the W12x16 Family for editing, and click on “Types” to open the “Family Types” dialogue box (Figure D-3);
5. Add a new parameter “Wrev” under the “Structural” to indicate the actual unit weight of the W12x16 beam to 26 pounds/ft. The “Wrev” is also a shared parameter stored in the Revit-LEED.txt.
6. Load the modified W12x16 back to the structural framing, and create a material takeoff for it;
7. Add the fields including “Assembly Code”, “Assembly Description”, “Family and Type”, “Cut Length”, “Material Cost”. Notice that the newly added shared parameter “Wrev” is now available since it is part of W12x26 type properties. Add another shared parameter “PostConsumer” from the Revit-LEED.txt (Figure D-4), since typical steel recycling is post-consumer;
8. Add a calculated value “Extended Cost” based on the formula that “Extended Cost = (Wrev / 2000 SF) * (Material: Cost * 1') * Cut Length”. This formula will compute the cost of a W12x26 steel beam with a unit weight of 26 pounds/ft and a unit material cost of $9000/ton;
9. Add another calculated value “RecycledValue” based on the formula that “RecycledValue = if (PostConsumer, Extended Cost * 0.25, 0)”. This formula will compute the value of recycled contents in the steel beams with a default recycled content percentage of 25% (recommended by USGBC). The “if” condition guarantees that only W12x26 with post-consumer recycled contents will be included in the calculation; and
10. Format the material takeoff to get the total value of the recycled contents of this structural framing (Figure D-5).

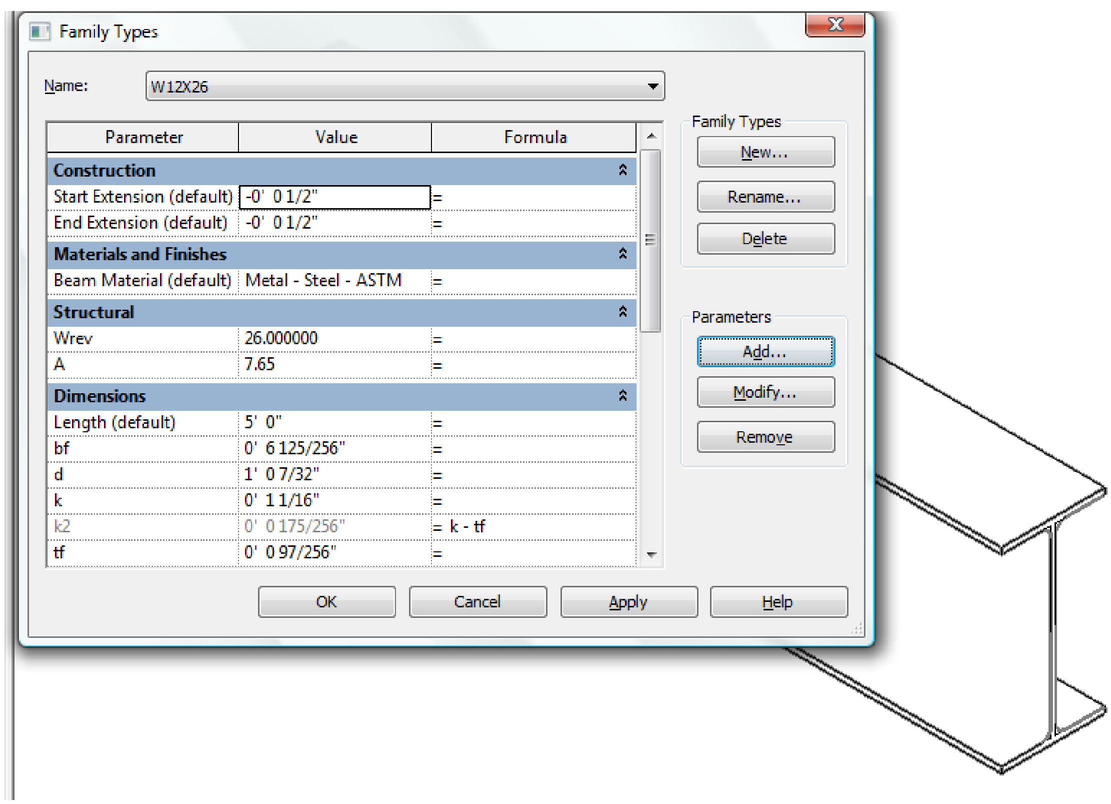


Figure D-3. Edit the steel beam family, and modify the “Family Types”

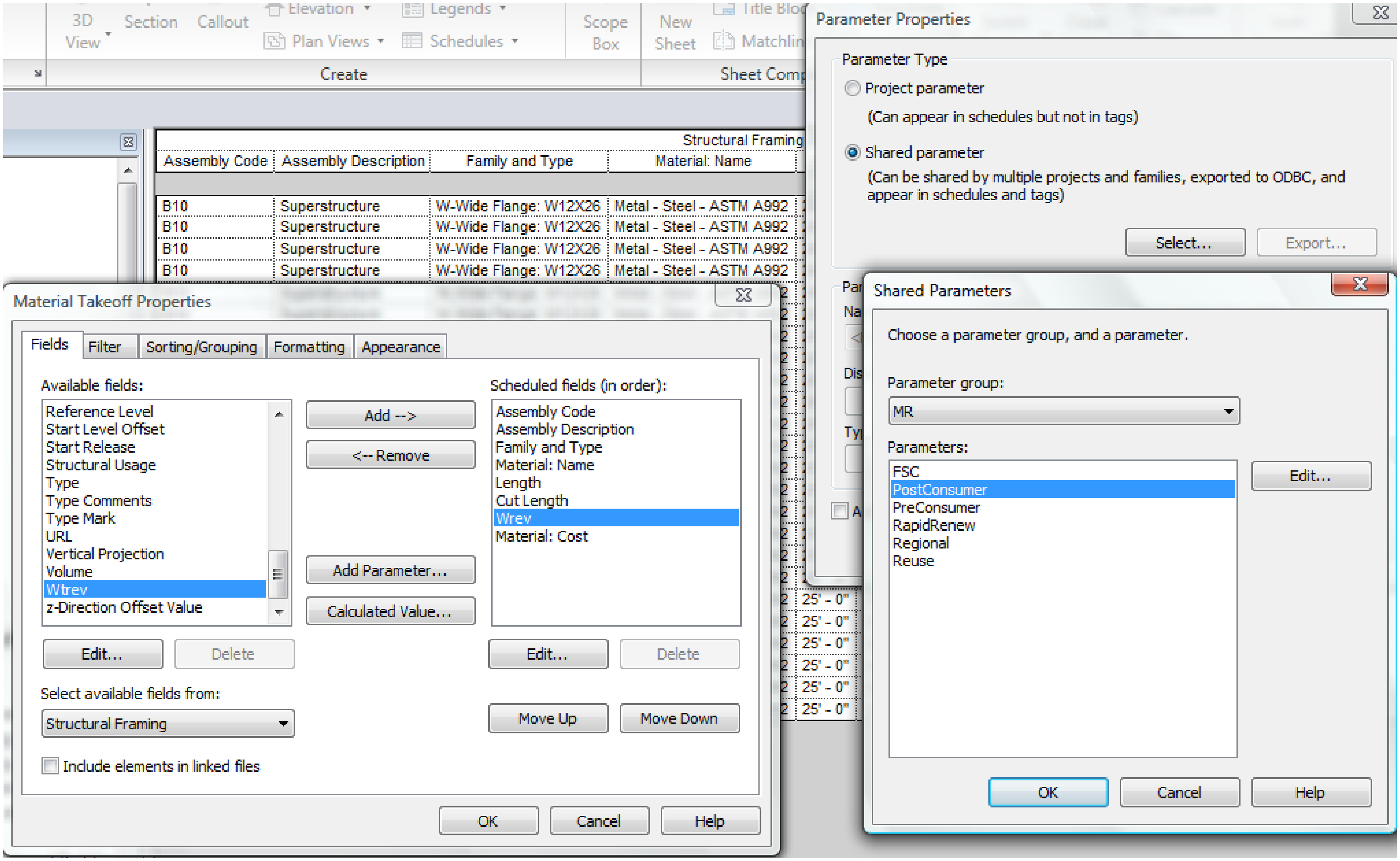


Figure D-4. Add proper fields into the structural framing material takeoff.

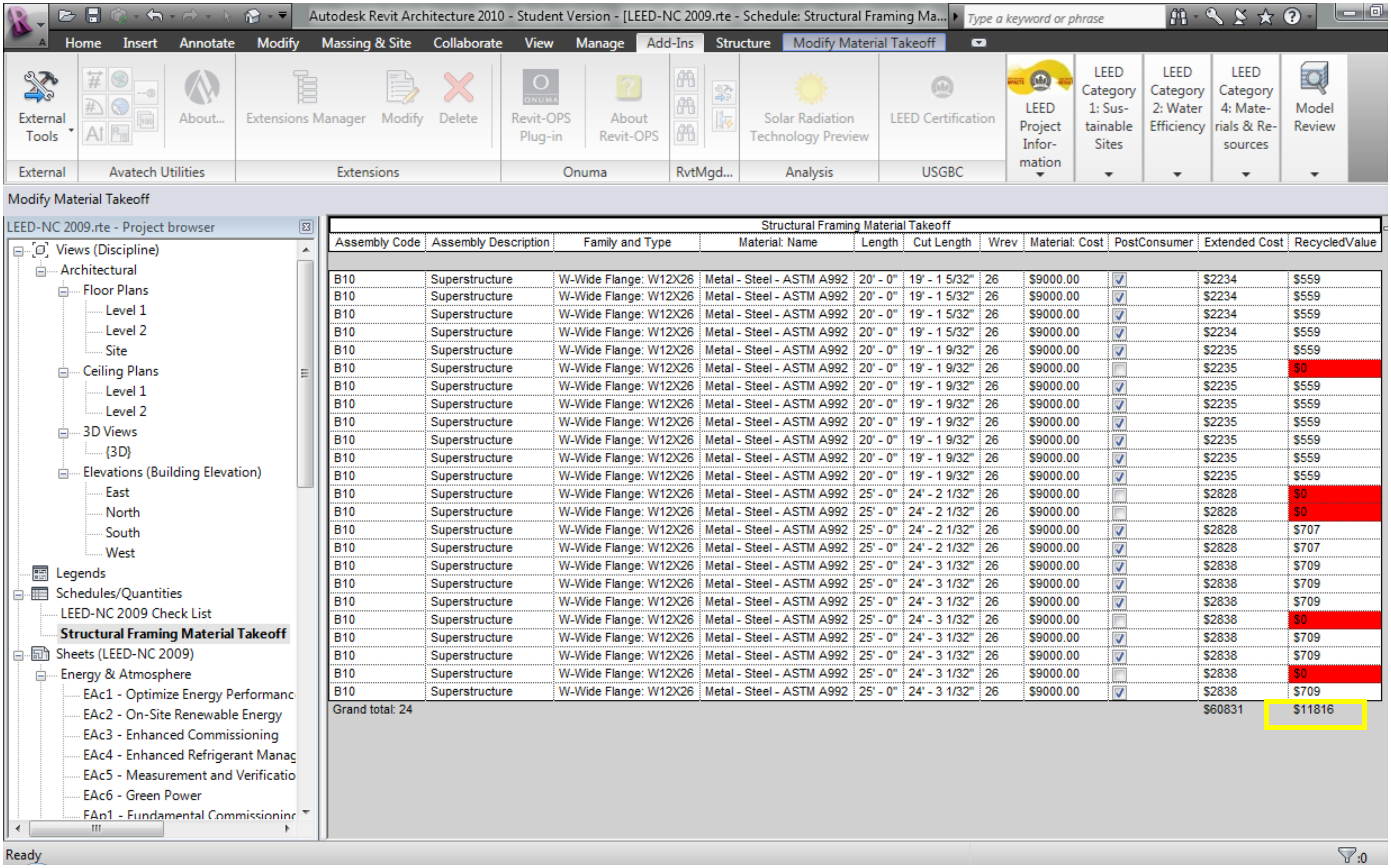
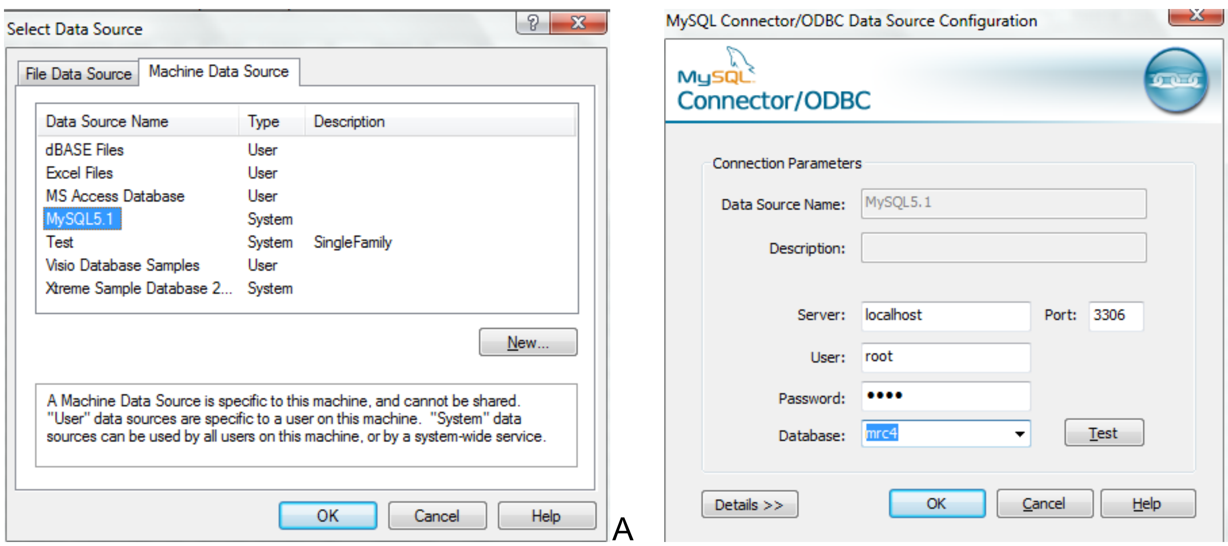


Figure D-5. Completed calculation for the MRc4: Recycled Contents of the sample structural framing.

APPENDIX E
DEMO: REVIT TO MYSQL VIA ODBC

Export Revit model data to MySQL through ODBC

1. Go to and select “Export”, click on “ODBC Database”;
2. In the “Select Data Source” dialogue box, select “Machine Data Source”, and select “MySQL5.1” (Figure E-1A), then click “OK”;
3. Specify the MySQL server information, and select the destination database (MRc4) to host the exported data (Figure E-1B), then click “OK”;



A

B

Figure E-1. Set up the ODBC export in Revit.

4. Open the MySQL Workbench to inspect the exported data from the sample model under the database MRc4. Notice that only the Revit predefined tables are presented, even most of them do not bear any data since only structural framing components are created in the sample model. The customized material takeoff for the structural framing is not exported;
5. However, it is still worth looking at the table “structuralframing”, and all the available fields exported. Obviously, none of the calculated recycled content values are exported; neither do the shared parameters created for the LEED calculations (Figure E-2).

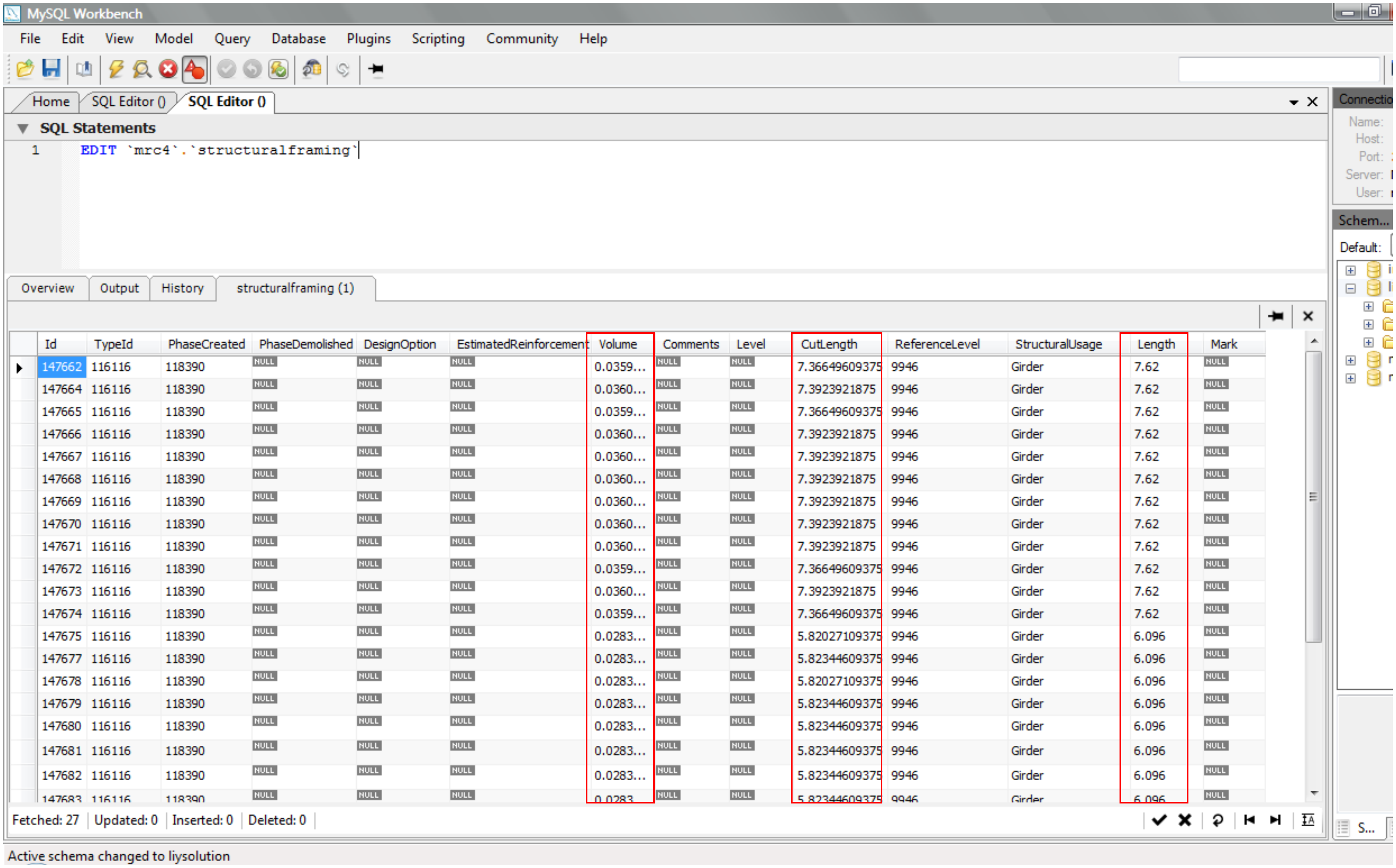


Figure E-2. Exported Revit model data in MySQL database

APPENIDIX F
DEMO: USE CASE MRC1 AND MRC2

Calculate MRc1 and MRc2 Using Phasing & Schedules/Quantities

1. Open a Revit file with existing building information. By default there are two phases created by Revit (‘Existing’ and ‘New Construction’). Check the “Element Properties” of all building components in current model to make sure the “Phase Created” are set as “Existing”, and the “Phase Demolished” set as “None”. Check the view properties of all the floor plans, elevation plans and 3D view, make sure the “Phase filter” set as “Show All” and the “Phases” set as “Existing”;
2. Make a copy of the floor plan (e.g. Level 1) where the building components will be demolished. Name the newly created floor plan as “Level 1 – Demolition”. Open the view properties of “Level 1 – Demolition” and set the “Phase filter” as “Show All” and the “Phases” as “New Construction”;
3. Use the “Demolish” command to demolish the building components that no longer needed (e.g. exterior wall and interior partitions), and construct the desired new components into the model (Figure F-1). Notice that demolished components will be marked in dotted lines and new construction will be highlighted in red, other unchanged existing building components are grayed out;
4. Make a copy of the finished floor plan, and name it as “Level 1 – Complete”. In its view properties, set the “Phase filter” as “Show Complete”, and the “Phases” as “New Construction” (Figure F-2);

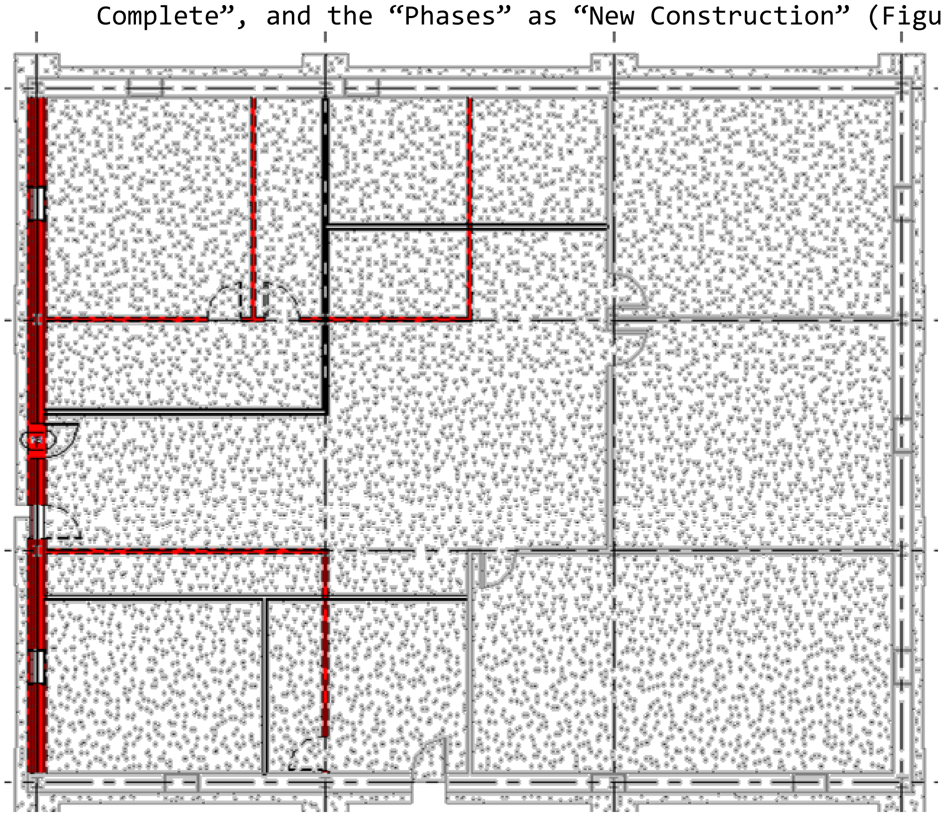


Figure F-1. Demolish and newly construct in Revit.

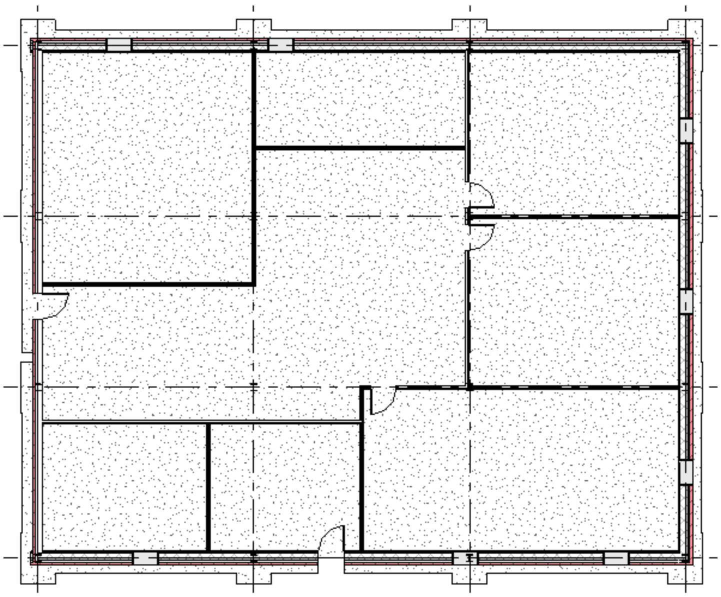


Figure F-2. Completed project floor plan.

5. Create a wall schedule, selecting the “Phase” as “Existing” (Figure F-3). Add these fields into the schedule: “Family and Type”, “Length”, “Width”, “Area” and “Volume”. Name the wall schedule as “Wall Schedule – Existing”;
6. Instead of creating a new wall schedule for the phase “New Construction”, simply make a copy of the existing wall schedule, modify the schedule’s properties and change the “Phase Filter” into “Show Complete” and the “Phase” into “New Construction”. Rename the duplicated wall schedule as “Wall Schedule – Complete”;
7. Make another duplicate of the wall schedule. This time name it as “Wall Schedule – New”. Set the “Phase Filter” as “Show New”, and the “Phase” as “New Construction”;
8. Tile the three wall schedules in the view window, notice the difference of the wall areas and wall volumes per family type (Figure F-4);

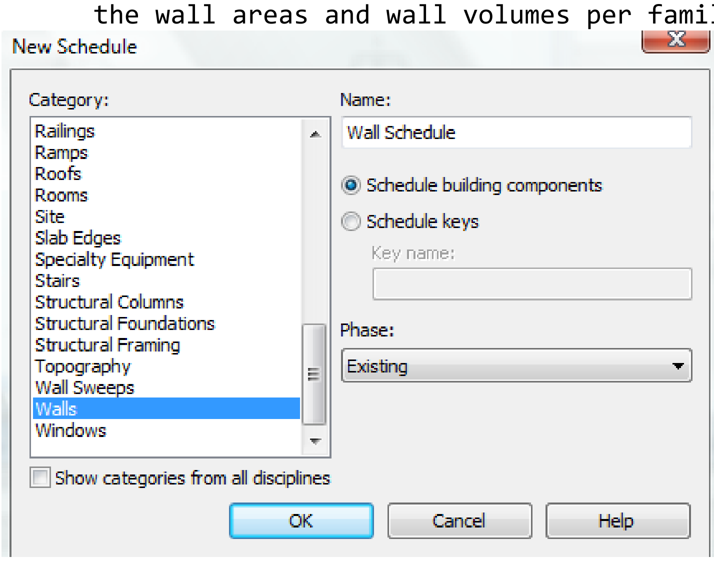
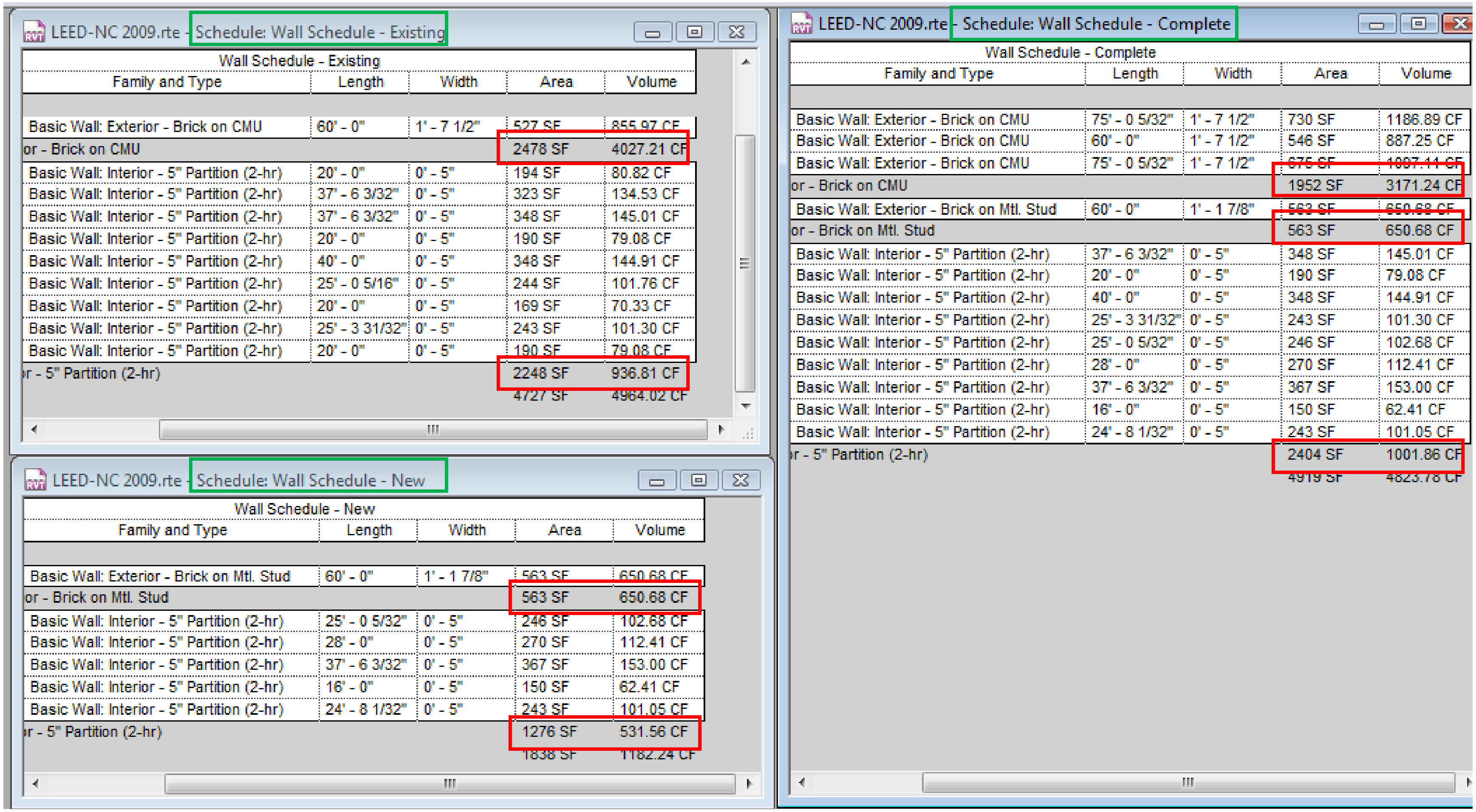


Figure F-3. Create a “Wall Schedule” for phase “Existing”.



LEED-NC 2009.rte - Schedule: Wall Schedule - Existing

Wall Schedule - Existing

Family and Type	Length	Width	Area	Volume
Basic Wall: Exterior - Brick on CMU	60' - 0"	1' - 7 1/2"	527 SF	855.97 CF
or - Brick on CMU			2478 SF	4027.21 CF
Basic Wall: Interior - 5" Partition (2-hr)	20' - 0"	0' - 5"	194 SF	80.82 CF
Basic Wall: Interior - 5" Partition (2-hr)	37' - 6 3/32"	0' - 5"	323 SF	134.53 CF
Basic Wall: Interior - 5" Partition (2-hr)	37' - 6 3/32"	0' - 5"	348 SF	145.01 CF
Basic Wall: Interior - 5" Partition (2-hr)	20' - 0"	0' - 5"	190 SF	79.08 CF
Basic Wall: Interior - 5" Partition (2-hr)	40' - 0"	0' - 5"	348 SF	144.91 CF
Basic Wall: Interior - 5" Partition (2-hr)	25' - 0 5/16"	0' - 5"	244 SF	101.76 CF
Basic Wall: Interior - 5" Partition (2-hr)	20' - 0"	0' - 5"	169 SF	70.33 CF
Basic Wall: Interior - 5" Partition (2-hr)	25' - 3 31/32"	0' - 5"	243 SF	101.30 CF
Basic Wall: Interior - 5" Partition (2-hr)	20' - 0"	0' - 5"	190 SF	79.08 CF
r - 5" Partition (2-hr)			2248 SF	936.81 CF
			4727 SF	4964.02 CF

LEED-NC 2009.rte - Schedule: Wall Schedule - New

Wall Schedule - New

Family and Type	Length	Width	Area	Volume
Basic Wall: Exterior - Brick on Mtl. Stud	60' - 0"	1' - 1 7/8"	563 SF	650.68 CF
or - Brick on Mtl. Stud			563 SF	650.68 CF
Basic Wall: Interior - 5" Partition (2-hr)	25' - 0 5/32"	0' - 5"	246 SF	102.68 CF
Basic Wall: Interior - 5" Partition (2-hr)	28' - 0"	0' - 5"	270 SF	112.41 CF
Basic Wall: Interior - 5" Partition (2-hr)	37' - 6 3/32"	0' - 5"	367 SF	153.00 CF
Basic Wall: Interior - 5" Partition (2-hr)	16' - 0"	0' - 5"	150 SF	62.41 CF
Basic Wall: Interior - 5" Partition (2-hr)	24' - 8 1/32"	0' - 5"	243 SF	101.05 CF
r - 5" Partition (2-hr)			1276 SF	531.56 CF
			1838 SF	1182.24 CF

LEED-NC 2009.rte - Schedule: Wall Schedule - Complete

Wall Schedule - Complete

Family and Type	Length	Width	Area	Volume
Basic Wall: Exterior - Brick on CMU	75' - 0 5/32"	1' - 7 1/2"	730 SF	1186.89 CF
Basic Wall: Exterior - Brick on CMU	60' - 0"	1' - 7 1/2"	546 SF	887.25 CF
Basic Wall: Exterior - Brick on CMU	75' - 0 5/32"	1' - 7 1/2"	675 SF	1097.11 CF
or - Brick on CMU			1952 SF	3171.24 CF
Basic Wall: Exterior - Brick on Mtl. Stud	60' - 0"	1' - 1 7/8"	563 SF	650.68 CF
or - Brick on Mtl. Stud			563 SF	650.68 CF
Basic Wall: Interior - 5" Partition (2-hr)	37' - 6 3/32"	0' - 5"	348 SF	145.01 CF
Basic Wall: Interior - 5" Partition (2-hr)	20' - 0"	0' - 5"	190 SF	79.08 CF
Basic Wall: Interior - 5" Partition (2-hr)	40' - 0"	0' - 5"	348 SF	144.91 CF
Basic Wall: Interior - 5" Partition (2-hr)	25' - 3 31/32"	0' - 5"	243 SF	101.30 CF
Basic Wall: Interior - 5" Partition (2-hr)	25' - 0 5/32"	0' - 5"	246 SF	102.68 CF
Basic Wall: Interior - 5" Partition (2-hr)	28' - 0"	0' - 5"	270 SF	112.41 CF
Basic Wall: Interior - 5" Partition (2-hr)	37' - 6 3/32"	0' - 5"	367 SF	153.00 CF
Basic Wall: Interior - 5" Partition (2-hr)	16' - 0"	0' - 5"	150 SF	62.41 CF
Basic Wall: Interior - 5" Partition (2-hr)	24' - 8 1/32"	0' - 5"	243 SF	101.05 CF
r - 5" Partition (2-hr)			2404 SF	1001.86 CF
			4919 SF	4823.78 CF

Figure F-4. Create wall schedules and assign them different phasing properties.

9. Now to calculate MRc1.1, the reused area percentage of exterior wall is computed as:

Percentage =
$$\frac{\{[\text{Exterior Wall Area (Complete)}]-[\text{Exterior Wall Area (New)}]\}}{[\text{Exterior Wall Area (Existing)}]} * 100\%$$

10. To calculate MRc1.2, the reused area percentage of interior wall is computed as:

Percentage =
$$\frac{\{[\text{Interior Wall Area (Complete)}]-[\text{Interior Wall Area (New)}]\}}{[\text{Interior Wall Area (Existing)}]} * 100\%$$

11. To calculate MRc2, the total construction waste generated is actually the demolished building components, of which the volume is:

Demolished Volume =
[Total Wall Volume (Existing)] - {[Total Wall Volume (Complete)]-[Total Wall Volume (New)]}

With supplemental information of the diverted construction waste (e.g. recycling proof and tipping fee invoices), the percentage of actual diverted construction waste can be calculated as:

$$\text{Percentage} = \frac{\text{Diverted Waste Volume} * 100\%}{\text{Total Construction Volume (Demolished Volume)}}$$

Calculate MRc3 – MRc7 Using Shared Parameters

1. Suppose that part of the wall bricks in this project are salvaged materials. To calculate MRc3: Material Reuse, a wall material takeoff is created with the shared parameter “Reuse”. Also some housekeeping needs to be done. By setting up a filter, only the bricks display in the wall material takeoff. The created wall material takeoff is shown in Figure G-1. The “Reused Value” is a calculated value that based on the following formula:
   Reused Value = if {Reuse, [Material: Cost]*[Material: Area/1’^2], 0};
   The “if” condition guarantees that only reused bricks are included into the calculation;

Wall Material Takeoff								
Assembly Code	Family and T	Material: Name	Material: Area	Material: Volume	Count	Material: Cost	Reuse	Reused Value
Basic Wall: Exterior - Brick on CMU								
B2010156	Basic Wal	Masonry - Brick	730 SF	220.64 CF	1	5.00	☑	$3651.96
B2010156	Basic Wal	Masonry - Brick	546 SF	164.94 CF	1	5.00	☑	$2730.00
B2010156	Basic Wal	Masonry - Brick	675 SF	203.95 CF	1	5.00	☑	$3375.71
Basic Wall: Exterior - Brick on Mtl. Stud								
B2010158	Basic Wal	Masonry - Brick	563 SF	170.00 CF	1	5.00	☐	$0.00
Grand total: 4								$9757.67

Figure G-1. Calculate MRc3 using shared parameter.

2. MRc4: Recycled Content has been c5overed in previous demo, so it will be skipped here;
3. Suppose that all the concrete used in this project are manufactured, retailed and transported within 500 miles, the project can pursue MRc5: Regional Materials. The material takeoff for all the concrete used in this project is created and the shared parameter “Regional” is used to perform the calculation. Figure G-2 summarizes the results;
4. Suppose that all the wall rigid insulation in this project use rapidly renewable agrifiber, the project could attempt MRc6: Rapidly Renewable Materials. Figure G-3 summarizes the computing material takeoff of the wall insulations, and the use of shared parameter “Regional”; and
5. Finally, all the flooring in the project uses FSC certified wood. The project decides to pursue MRc7: FSC certified wood. With the use of shared parameter “FSC”, the value of FSC certified wood could then be computed. Figure G-4 summarizes the calculation for MRc7;

Structural Foundation Material Takeoff							
Assembly Code	Family and Type	Material: Name	Material: Area	Material: Volume	Material: Cos	Regiona	Regional Value
Foundation Slab: 6" Foundation Slab							
	Foundation Slab: 6" Foundation Slab	Concrete - Cast-in-Place Concrete	4504 SF	2251.83 CF	2.80	☑	$6305.13
Footing-Rectangular: 72" x 48" x 18"							
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	78 SF	32.95 CF	2.80	☑	$92.27
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	75 SF	29.98 CF	2.80	☑	$83.94
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	75 SF	29.98 CF	2.80	☑	$83.94
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	78 SF	32.97 CF	2.80	☑	$92.33
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	76 SF	29.93 CF	2.80	☑	$83.79
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	68 SF	24.00 CF	2.80	☑	$67.20
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	68 SF	24.00 CF	2.80	☑	$67.20
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	76 SF	29.97 CF	2.80	☑	$83.91
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	76 SF	29.93 CF	2.80	☑	$83.79
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	68 SF	24.00 CF	2.80	☑	$67.20
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	68 SF	24.00 CF	2.80	☑	$67.20
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	76 SF	29.97 CF	2.80	☑	$83.91
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	78 SF	32.95 CF	2.80	☑	$92.27
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	75 SF	29.98 CF	2.80	☑	$83.94
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	75 SF	29.98 CF	2.80	☑	$83.94
A1010100	Footing-Rectangular: 72" x 48" x 18"	Concrete - Cast-in-Place Concrete	78 SF	32.97 CF	2.80	☑	$92.33
Wall Foundation: Retaining Footing - 24" x 12" x 12"							
A1010110	Wall Foundation: Retaining Footing - 24" x 12" x 12"	Concrete - Cast-in-Place Concrete	701 SF	192.81 CF	2.80	☐	$0.00
A1010110	Wall Foundation: Retaining Footing - 24" x 12" x 12"	Concrete - Cast-in-Place Concrete	521 SF	138.46 CF	2.80	☐	$0.00
A1010110	Wall Foundation: Retaining Footing - 24" x 12" x 12"	Concrete - Cast-in-Place Concrete	719 SF	199.89 CF	2.80	☐	$0.00
A1010110	Wall Foundation: Retaining Footing - 24" x 12" x 12"	Concrete - Cast-in-Place Concrete	523 SF	140.00 CF	2.80	☐	$0.00
Grand total: 21				3390.55 CF			$7614.30

Figure G-2. Calculate MRc5 using shared parameter.

Wall Material - Insulation Takeoff								
Assembly Code	Family and T	Material: Name	Material: Area	Material: Volume	Count	Material: Cost	RapidRenew	RapidRenew
Basic Wall: Exterior - Brick on CMU								
B2010156	Basic Wal	Insulation / Thermal Barriers - Rigid insulation	730 SF	182.60 CF	1	1.80	☑	$1314.70
B2010156	Basic Wal	Insulation / Thermal Barriers - Rigid insulation	546 SF	136.50 CF	1	1.80	☑	$982.80
B2010156	Basic Wal	Insulation / Thermal Barriers - Rigid insulation	675 SF	168.79 CF	1	1.80	☑	$1215.25
Grand total: 3			1952 SF					$3512.76

Figure G-3. Calculate MRc6 using shared parameter.

Floor Material Takeoff						
Assembly Code	Family and Type	Material: Area	Material: Volume	Material: Cost	FSC	FSC Value
Floor: Wood Flooring - 2"						
B1010	Floor: Wood Flooring - 2"	4298 SF	716.30 CF	2.00	☑	$8595.55
Grand total: 1		4298 SF				$8595.55

Figure G-4. Calculate MRc7 using shared parameter.

APPENDIX H
SAMPLE CODES: REVIT – LEED APPLICATION MODEL

Create Application Inheriting IExternalCommand

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using Autodesk.Revit;
using System.Windows.Forms;
using System.Diagnostics;
using System.IO;

namespace LeedCertification
{
    public class MRp1RatingSystem:IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRp1RatingSystem
.pdf");

            return IExternalCommand.Result.Succeeded;
        }
    }

    public class MRp1Template:IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRp1Template.pdf
");

            return IExternalCommand.Result.Succeeded;
        }
    }

    //

    public class MRc1aRatingSystem:IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc1.1-
1.2RatingSystem.pdf");
```

```
            return IExternalCommand.Result.Succeeded;
        }
    }

    public class MRc1aTemplate:IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc1.1-
1.2Template.pdf");

            return IExternalCommand.Result.Succeeded;
        }
    }

    //

    public class MRc1bRatingSystem:IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc1.3RatingSyst
em.pdf");

            return IExternalCommand.Result.Succeeded;
        }
    }

    public class MRc1bTemplate:IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc1.3Template.p
df");

            return IExternalCommand.Result.Succeeded;
        }
    }

    //

    public class MRc2RatingSystem:IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
```

```
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc2RatingSystem
.pdf");

            return IExternalCommand.Result.Succeeded;
        }
    }

    public class MRc2Template : IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc2Template.pdf
");

            return IExternalCommand.Result.Succeeded;
        }
    }

    //

    public class MRc3RatingSystem:IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc3RatingSystem
.pdf");

            return IExternalCommand.Result.Succeeded;
        }
    }

    public class MRc3Template : IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc3Template.pdf
");

            return IExternalCommand.Result.Succeeded;
        }
    }

    //
```

```
    public class MRc4RatingSystem:IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc4RatingSystem
.pdf");

            return IExternalCommand.Result.Succeeded;
        }
    }

    public class MRc4Template : IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc4Template.pdf
");

            return IExternalCommand.Result.Succeeded;
        }
    }

    //

    public class MRc5RatingSystem:IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc5RatingSystem
.pdf");

            return IExternalCommand.Result.Succeeded;
        }
    }

    public class MRc5Template : IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc5Template.pdf
");

            return IExternalCommand.Result.Succeeded;
        }
```

```
    }

    //

    public class MRc6RatingSystem:IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc6RatingSystem
.pdf");

            return IExternalCommand.Result.Succeeded;
        }
    }

    public class MRc6Template : IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc6Template.pdf
");

            return IExternalCommand.Result.Succeeded;
        }
    }

    //

    public class MRc7RatingSystem:IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {

System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc7RatingSystem
.pdf");

            return IExternalCommand.Result.Succeeded;
        }
    }

    public class MRc7Template : IExternalCommand
    {
        public IExternalCommand.Result Execute(ExternalCommandData commandData,
        ref string message, ElementSet elements)
        {
```

```
System.Diagnostics.Process.Start(@"C:\REVITLEED\LEEDTemplates\MR\MRc7Template.pdf
");

            return IExternalCommand.Result.Succeeded;
        }
    }
}
```

Create Host Panels Inheriting IExternalApplication

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using Autodesk.Revit;
using System.Windows.Media.Imaging;

namespace AddPanel
{
    public class CsAddpanel:IExternalApplication
    {
        public IExternalApplication.Result OnStartup(ControlledApplication
application)
        {
            string assembly =
@"C:\REVITLEED\LeedCertification\LeedCertification\bin\Debug\LeedCertification.dl
l";

            RibbonPanel mrPanel = application.CreateRibbonPanel("LEED Category 4:
Materials & Resources");

            PulldownButton MRp1 = mrPanel.AddPulldownButton("Prerequsite 1",
"Prerequisite 1");

            PushButton MRp1RatingSystem = MRp1.AddItem("RatingSystem", assembly,
"LeedCertification.MRp1RatingSystem");

            PushButton MRp1Template = MRp1.AddItem("Template", assembly,
"LeedCertification.MRp1Template");

            mrPanel.AddSeparator();

            PulldownButton MRc1a = mrPanel.AddPulldownButton("Credit 1.1-1.2",
"Credit 1.1-1.2");

            PushButton MRc1aRatingSystem = MRc1a.AddItem("RatingSystem",
assembly, "LeedCertification.MRc1aRatingSystem");

            PushButton MRc1aTemplate = MRc1a.AddItem("Template", assembly,
"LeedCertification.MRc1aTemplate");
```

```
            PulldownButton MRc1b = mrPanel.AddPulldownButton("Credit 1.3",
"Credit 1.3");

            PushButton MRc1bRatingSystem = MRc1b.AddItem("RatingSystem",
assembly, "LeedCertification.MRc1bRatingSystem");

            PushButton MRc1bTemplate = MRc1b.AddItem("Template", assembly,
"LeedCertification.MRc1bTemplate");

            PulldownButton MRc2 = mrPanel.AddPulldownButton("Credit 2", "Credit
2");
            PushButton MRc2RatingSystem = MRc2.AddItem("RatingSystem", assembly,
"LeedCertification.MRc2RatingSystem");

            PushButton MRc2Template = MRc2.AddItem("Template", assembly,
"LeedCertification.MRc2Template");

            PulldownButton MRc3 = mrPanel.AddPulldownButton("Credit 3", "Credit
3");
            PushButton MRc3RatingSystem = MRc3.AddItem("RatingSystem", assembly,
"LeedCertification.MRc3RatingSystem");

            PushButton MRc3Template = MRc3.AddItem("Template", assembly,
"LeedCertification.MRc3Template");

            PulldownButton MRc4 = mrPanel.AddPulldownButton("Credit 4", "Credit
4");
            PushButton MRc4RatingSystem = MRc4.AddItem("RatingSystem", assembly,
"LeedCertification.MRc4RatingSystem");

            PushButton MRc4Template = MRc4.AddItem("Template", assembly,
"LeedCertification.MRc4Template");

            PulldownButton MRc5 = mrPanel.AddPulldownButton("Credit 5", "Credit
5");
            PushButton MRc5RatingSystem = MRc5.AddItem("RatingSystem", assembly,
"LeedCertification.MRc5RatingSystem");

            PushButton MRc5Template = MRc5.AddItem("Template", assembly,
"LeedCertification.MRc5Template");

            PulldownButton MRc6 = mrPanel.AddPulldownButton("Credit 6", "Credit
6");
            PushButton MRc6RatingSystem = MRc6.AddItem("RatingSystem", assembly,
"LeedCertification.MRc6RatingSystem");

            PushButton MRc6Template = MRc6.AddItem("Template", assembly,
"LeedCertification.MRc6Template");

            PulldownButton MRc7 = mrPanel.AddPulldownButton("Credit 7", "Credit
7");
```

```
            PushButton MRc7RatingSystem = MRc7.AddItem("RatingSystem", assembly,
"LeedCertification.MRc7RatingSystem");

            PushButton MRc7Template = MRc7.AddItem("Template", assembly,
"LeedCertification.MRc7Template");

            return IExternalApplication.Result.Succeeded;
        }

        public IExternalApplication.Result OnShutdown(ControlledApplication
application)
        {
            return IExternalApplication.Result.Succeeded;
        }
    }
}
```

Create Distance Calculator Using Zip Codes

```
using System;
using System.Collections.Generic;
using System.Text;
using System.IO;
using System.Xml.Serialization;

namespace ZipDistCalculator
{
    public class ZipCode
    {

        private string _state;
        private string _code;
        private double _latitude;
        private double _longitude;

        public double Longitude
        {
            get { return _longitude; }
            set { _longitude = value; }
        }

        public double Latitude
        {
            get { return _latitude; }
            set { _latitude = value; }
        }

        public string Code
        {
            get { return _code; }
            set { _code = value; }
        }
```

```
        public string State
        {
            get { return _state; }
            set { _state = value; }
        }

        #region Static methods/variables
        private static List<ZipCode> _codeList;

        public static List<ZipCode> CodeList
        {
            get { return _codeList; }
            set { _codeList = value; }
        }

        public static void LoadData(string path)
        {
            if (File.Exists(path))
            {
                using (StreamReader reader =
                    new
StreamReader(@"C:\REVITLEED\ZipDistance\ZipDistCalculator\ZipDistCalculator\ZipCo
deData.xml"))
                {
                    XmlSerializer serializer =
                        new XmlSerializer
                            (typeof(List<ZipCode>));

                    _codeList =
                        (List<ZipCode>)
                        serializer.Deserialize(reader);
                }
            }
            else
            {
                throw new
                    FileLoadException
                    ("Can't find ZipCodeData.xml!");
            }
        }

        public static double Distance(string zipCode1,
                                      string zipCode2)
        {
            ZipCode code1 = _codeList.Find(
                            delegate(ZipCode z)
                            {
                                return z.Code == zipCode1;
                            });

            ZipCode code2 = _codeList.Find(
```

```
                    delegate(ZipCode z)
                    {
                        return z.Code == zipCode2;
                    });

            if (code1 == null || code2 == null)
                throw new ArgumentException
                    ("One of the codes does not exist.");

            double earthsRadius = 3956.087107103049;

            double latitude1Radians =
                (code1.Latitude / 180) * Math.PI;

            double longitude1Radians =
                (code1.Longitude / 180) * Math.PI;

            double latitude2Radians =
                (code2.Latitude / 180) * Math.PI;

            double longitude2Radians =
                (code2.Longitude / 180) * Math.PI;

            double distance =
                (earthsRadius * 2) *
                Math.Asin(
                 Math.Sqrt(
                  Math.Pow(
                   Math.Sin((latitude1Radians -
                             latitude2Radians) / 2), 2) +
                  Math.Cos(latitude1Radians) *
                  Math.Cos(latitude2Radians) *
                  Math.Pow(
                   Math.Sin((longitude1Radians -
                             longitude2Radians) / 2), 2)
                 )
                );

            return distance;
        }
        #endregion
    }
}
```

LIST OF REFERENCES

ANSI. (2010). “ANSI/GBI Standard.” ANSI, <http://www.thegbi.org/green-globes/ansi-gbi-standard.asp> (May 30, 2010).

ASHRAE. (2010). “The Green Standard: Standard 189.1.” ASHRAE, <http://www.ashrae.org/publications/page/927> (May 30, 2010).

Autodesk. (2005). “Building Information Modeling for Sustainable Design.” Autodesk, <http://images.autodesk.com/adsk/files/bim_for_sustainable_design_jun05.pdf> (Jan.18, 2009).

Autodesk. (2008). “BIM and the Autodesk Green Building Studio.” Autodesk, <http://images.autodesk.com/adsk/files/bim_and_the_autodesk_green_building_studio_2008.pdf> (Jan.18, 2009).

Autodesk. (2009). “Design without compromise.” Autodesk, <http://images.autodesk.com/adsk/files/revit_architecture_2010_brochure.pdf> (Jan.10, 2009).

Autodesk. (2009). “Revit 2010 API: Developer’s Guide, Version 1.0.” Autodesk, <http://usa.autodesk.com/adsk/servlet/index?siteID=123112andid=2484975> (Nov.18, 2009).

Bell, H., and Bjørkhanug, L. (2006). eWork and eBusiness in Architecture, Engineering and Construction (Martinez, M., and Scherer, R., eds.), A buildingSMART ontology, 185-190, Taylor and Francis, London.

Barnes, S., and Castro-Lacouture, D. (2009). BIM-enabled Integrated Optimization Tool for LEED Decisions, Proceedings, International Workshop on Computing in Civil Engineering, ASCE, Austin, TX.,258-268.

Biswas, T., Wang,T.H., and Krishnamurti, R. (2008). Integrating sustainable building rating systems with building information models, Proceedings, 13th International Conference on Computer Aided Architectural Design Research in Asia, CAADRIA, Chiang Mai,Thailand, 193-200.

CIB. (1999). Agenda 21 on sustainable construction, CIB Report Publication 237, Rotterdam, The Netherlands.

CRISP. (2002). “A European Thematic Network on Constructions and City Related Sustainability Indicators.” CRISP, <http://crisp.cstb.fr/PDF/CRISP_Final_Report.pdf> (Jan.10, 2009).

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2008). BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, 1st Ed., Wiley, Hoboken, New Jersey.

Fowler, K.M., and Rauch, E.M. (2006). “Sustainable Building Rating Systems Summary, Technical Report PNNL-15858, Pacific Northwest National Laboratory, Department of Energy”, USGBC, <https://www.usgbc.org/ShowFile.aspx?DocumentID=1915> (Dec.18, 2008)

Gallaher, M.P., O’Connor, A.C., Dettbarn, J.L., and Gilday, L.T. (2004). Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry, National Institute of Standards and Technology, Gaithersburg, Maryland.

GBCI. (2009). “LEED 2009 Minimum Program Requirements.” GBCI, <https://www.usgbc.org/ShowFile.aspx?DocumentID=6715> (Jan.18, 2009).

GBS. (2009). “Autodesk Green Building Studio.” Autodesk, <https://www.greenbuildingstudio.com/Account.mvc/Login> (Jan.18, 2009).

gbXML. (2009). “Open Green Building XML Schema: a Building Information Modeling Solution for Our Green World.” <http://www.gbxml.org/> (Jan.18, 2009).

Gillard, A., Counsell, J.A.M., and Littlewood, J.R. (2008). “The Atlantic College case study - exploring the use of BIM for the sustainable design and maintenance of property.” <http://www.rics.org/site/download_feed.aspx?fileID=3115andfileExtension=PDF> (Jan.18, 2009).

GSA. (2008). “3D-4D Building Information Modeling.” GSA, <http://www.gsa.gov/bim> (Dec.18, 2008).

Guy, G.B., and Kibert, C.J. (1998). “Developing Indicators of Sustainability: U.S. Experience.” Proceeding, the Second International Conference on Buildings and the Environment (2), Paris, France, 549-556.

Haagenrud, S.E. (2007). “Integration of performance based building standards into business processes using open IFC standards to enhance innovation and sustainable development.” Europe-Innova, <http://standards.eu-innova.org/Files/Conference/04152008/presentation_Stand-INN_CEN07.pdf> (Feb.12, 2009).

Häkkinen, T. (2007). “ISO/TC59/SC17 N 236 - Building construction/Sustainability in building construction/Sustainability Indicators, WG2 Sustainability Indicators.” <http://217.197.210.21/resources/sustainability/ISO-TC059-SC17_N0236_Draft_of_New_Work_Item_Proposal_-_Susta.pdf> (Dec.12, 2008).

Haynes, D. (2008). “Revit Architecture – LEEDing the Way: Additional Materials.” Autodesk, <http://au.autodesk.com/ama/images/media/AB204-2-Revit-Architecture-LEEDing_Additional-Materials.pdf> (Jan.18, 2009).

Huang, Y.C., Lam, K.P. and Dobbs, G. (2008). “A Scalable Lighting Simulation Tool for Integrated Building Design.” Proceedings, Third National Conference of IBPSA-USA, Berkeley, California.

IAI. (2009). “Industry Foundation Class: IFC 2x Edition 4 beta 3 version.” IAI, <http://www.iai-tech.org/ifc/IFC2x4/beta3/html/index.htm> (Dec.18, 2009)

ICC. (2010). “International Green Construction Code.” ICC, <http://www.iccsafe.org/cs/IGCC/Pages/default.aspx> (May.30, 2010).

IES. (2009). “Powerful New Solutions for Sustainable Design.” IES, <http://www.iesve.com/content/mediaassets/pdf/REVIT%20PLUG-IN%20UK%20%28VE6%29.pdf> (Dec.18, 2009).

IES/Revit. (2010). “BIM+Building Performance Analysis Using Revit 2010 and IES<Virtual Environment>.” IES, <http://www.iesve.com/content/mediaassets/pdf/Revit%202010_Guidance.pdf> (Jan.18, 2010).

ISO. (2006). ISO/TS 21929-1:2006(E) Sustainability in building construction — Sustainability indicators — Part 1: Framework for the development of indicators for buildings, ISO, Geneva, Switzerland.

Jernigan, F. (2007). BIG BIM little bim, 1st Ed., Site Press, Salisbury, MD.

Khemlani, L. (2004). “The IFC Building Model: A Look under the Hood.” AECbytes, <http://www.aecbytes.com/feature/2004/IFCmodel.html> (Dec. 12, 2008).

Kibert, C.J. (1994). “Establishing Principles and a Model for Sustainable Construction.” Proceedings, the First International Conference on Sustainable Construction, Tampa, Florida, 1-9.

Kiviniemi, A., Tarandi, V., Karlshøj, J., Bell, H., and Karud, O.J. (2008). Review of the Development and Implementation of IFC Compatible BIM, Danish Enterprises and Construction Authority, the Research Council of Norway.

Krygiel, E., and Nies, B. (2008). Green BIM: Successful Sustainable Design with Building Information Modeling, 1st Ed., Wiley, Indianapolis, Indiana.

Laine, T., and Karola, A. (2007). “Benefits of Building Information Models in Energy Analysis.” Proceedings, Clima 2007 WellBeing Indoors. Olof Granlund Oy, Helsinki, Helsinki, Finland.

McGraw-Hill Construction. (2008). “SmartMarket Report – Building Information Modeling (BIM): Transforming Design and Construction to Achieve Greater Industry Productivity.” <http://construction.ecnext.com/mcgraw_hill/includes/BIM2008.pdf> (Jan.18, 2009).

McGraw-Hill Construction. (2009). “SmartMarket Report – The Business Value of BIM: Getting Building Information Modeling to the Bottom Line.” <http://www.nibs.org/client/assets/files/bsa/mhc_bim_smartmarket1109.pdf> (Jan.22, 2010).

NBIMS Committee. (2007). “United States National Building Information Modeling Standard, Version 1.” WBDG, <http://www.wbdg.org/pdfs/NBIMSv1_p1.pdf> (Nov.15, 2008).

Nisbet, N., and Liebich, T. (2007). “ifcXML Implementation Guide, Version 2.0.” IAI, <http://www.iai-tech.org/downloads/accompanying-documents/guidelines/ifcXML%20Implementation%20Guide%20v2-0.pdf/index_html> (Jan 18. 2009).

Public Technology Inc. (1996). “Sustainable Building Technical Manual – Green Building Design, Construction and Operations.” USGBC, <https://www.usgbc.org/Docs/SBTM/sbt.pdf> (Jan.18, 2009).

Rundell, R. (2008). “BIM and Green Building Studio – 1-2-3 Revit Tutorial.” Cadalyst, <http://www.cadalyst.com/aec/bim-and-green-building-studio-1-2-3-revit-tutorial-3755> (Jan.18, 2009).

Schlueter, A., and Thesseling, F. (2008). “Building information model based energy/exergy performance assessment in early design stage.” Automation in Construction, 18(2), 153-163.

Sjøgren, J. (2007). “Introduction to buildingSMART.” buildingSMART, <http://www.buildingsmart.no/> (Dec.18, 2008).

Smith, D.K., and Tardif, M. (2009). Building Information Modeling: A Strategic Implementation Guide for Architects, Engineers, Constructors, and Real Estate Asset Managers, 1st Ed., John Wiley and Sons, Hoboken, New Jersey.

Smith, Z. (2008). “How do I determine the distance between ZIP codes using C#?” <http://blogs.techrepublic.com.com/programming-and-development/?p=634> (Jan.10, 2010).

STAND-INN. (2007). “IFC Support for Sustainability.” Eu-Innova, <http://standards.eu-innova.org/Files/Report/STAND-INN_D13_IFC_support_for_sustainability.pdf> (Feb.12, 2009).

Teicholz, P. (2004). “Labor Productivity Declines in the Construction Industry: Causes and Remedies.” Aecbytes, <http://www.aecbytes.com/viewpoint/2004/issue_4.html> (Dec.18, 2008).

Teo, A.L., and Cheng, T.F. (2005). “Building Smart – A Strategy for Implementing BIM Solution in Singapore.” <http://www.itsc.org.sg/pdf/5_BIM.pdf> (Jan. 28, 2009).

Udall, R., and Schendler, A. (2005). “LEED is Broken - Let's Fix It.” <http://www.igreenbuild.com/cd_1706.aspx> (Dec.18, 2008).

UNEP. (2006). “United Nations Environment Program: Sustainable Buildings and Climate Initiative.” UNEP, <http://www.unep.org/sbci/AboutSBCI/Background.asp> (Dec.18, 2008).

USGBC. (2007). LEED for New Construction Reference Guide, Version 2.2, 3rd Ed., U.S. Green Building Council, Washington DC.

USGBC. (2009). “Green Building Facts.” USGBC, <http://www.usgbc.org/ShowFile.aspx?DocumentID=5961> (Nov.12, 2009).

WBDG. (2010). “Continuing Education: WBDG01-The Integrated Design Process.” WBDG, <http://www.wbdg.org/education/integrated_design.php> (Jan.18, 2010).

BIOGRAPHICAL SKETCH

Wei Wu received his Bachelor of Engineering degree in Built Environment and Equipment Engineering at Hunan University in China in 2004. He proceeded to conduct his master's study in Environmental Change and Management at University of Oxford in the UK, one of the most prestigious universities in the world, and obtained the Master of Science degree in 2005. In 2006 he married Can Liu, an angel he had been dating since thirteen, in London. Also in 2006, he decided to pursue his doctoral degree with a clear interest in the green building and sustainable construction. He was then admitted to M.E. Rinker, Sr. School of Building Construction at the University of Florida and awarded a 4-year Alumni Fellowship. During his study and research at Rinker, Wei Wu gained substantial academic and industrial experience through teaching, research and internships. Based on his superior academic performance, he was awarded the Certificate of Outstanding Academic Achievement in 2008. The same year, he was recruited by Hawkins Construction, Inc. for a summer internship, during which he obtained comprehensive construction experience. At the end of 2008, he selected his current dissertation topic and literally found his career in the integration of BIM and sustainability. Wei and Can enjoyed the sunshine in Florida. The time at Rinker has been one of the most important stages in their life. Now Wei has fulfilled his academic goals, and he and Can together are ready for any coming adventure.