Towards a Framework for Supporting Sustainable Building Design: *A case study of two credits over evolving rating standards*

DISSERTATION

Submitted for consideration in partial fulfillment of the requirements

for the degree of Doctor of Philosophy

in Architecture Engineering and Construction Management

by

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ABSTRACT

It is becoming increasingly relevant that designs address sustainability requirements. The objectives of any sustainable design are: to reduce resource depletion of energy, water, and raw materials; prevent environmental degradation caused throughout the building lifecycle; provide a safe, comfortable and healthy living environment. Currently, the sustainability of a building is judged by standards codified in a rating system. [1] Although compliance with a sustainability rating system is not mandatory, increasingly, it is becoming a goal that many designers and authorities would like to achieve.

However, there are impediments to the pervasive use of sustainable design rating systems.

1. Certification is expensive. [2] It is labor intensive, involving large volumes of data aggregation, information accounting and exchange, which, can be a deterrent to designers and the design process.
2. Ratings systems are periodically reviewed; as our understanding increase and technology improve, sustainability requirements on designs become more extensive and, sometimes, more stringent. [3]
3. Sustainable building design rating tools are not readily integrated into the design process whereby the design solution can be developed by different disciplines.

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(1) Design choices are validated, by measuring design performance against criteria specified by the rating system. See Chapter 2: Research Background.

(2) "Shame on you for perpetuating this myth that green design costs more even if integrated properly. LEED certification does, but green design need not." (Kats, 2010)

(3) "Sustainability is not static–it is iteratively changing, based on knowledge that connects science and design." (Williams, 2007)

4. The design information model associated with a building may not contain the data (attributes) necessary to evaluate its design.
5. Information is disparate and distributed—requiring it to be supplemented, augmented from various sources, and managed for the different stages of a building design process

In practice, designers tend to employ commercial (and reasonably stable) design tools, making it imperative to develop an approach that utilizes information readily and currently available in digital form in conjunction with rating system requirements. This research focuses on supporting sustainability assessment where designers need to evaluate the information in a design in order to fulfill sustainability metrics.

The main research objective is an approach to integrating sustainability assessment with a design environment. This comprises: identifying informational requirements from rating systems; representing them in computable form; mapping them to information in a commercial design tool; and assessing the performance of a design. An overall framework for organizing, managing and representing sustainability information requirements is developed as the demonstrator.

Case study of an actual project demonstrates the flow of information from a commercially available building information modeler and a sustainable building rating system. The process developed bridges sustainability assessment requirements with information from the model for pre-evaluation prior to submission for certification.

Contributions include a technical implementation of sustainable design assessment for pre assessment through a process of identifying information availability, augmentation, representation and management focused on two credits (Reduce indoor water use and Minimum energy performance) over evolving rating standards, namely (LEED 2.1, LEED 2009 and LEED v4). These contributions are intended to enable designers, stakeholders, contractors and other professionals to communicate strategies and make informed decisions to achieve sustainability goals for a project from design through to operation.

Keywords: Sustainable building rating systems, building information modeling.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

"Building information modeling (BIM) is an emerging tool in the design industry…it has the ability to help guide the industry in a more sustainable direction by allowing easier access to tools necessary to quantify a greener design approach."
(Krygiel & Nies, 2008)

Buildings and designs that address environmental issues, more commonly known as 'sustainable' [4] or 'green' buildings are becoming increasingly desirable, both as expressions of owner expectation and as design products. Currently and commonly, buildings are deemed sustainable by certification (e.g., by an authority such as by LEED [5], BREEAM [6] or an appropriate sustainable building rating system) (Cole, 1999) (Gissen, 2003). There are several ways of targeting sustainability in buildings, for example, through a pragmatic approach and well-managed processes (Williams L. , 2010). To this end digital design technologies are almost universally adopted as the predominant means of production in current architectural practice (Kotnik, 2010). Design tools such as building information models (BIM) have paved the way for developing, storing, and updating design data, however, many of the strategies, old or new, are not directly accessible within a BIM itself (Krygiel & Nies, 2008). It is in the context of technology with which this dissertation

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(4) The general definition of sustainability is 'the development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs'. (Brundtland, 1987)

(5) Leadership in Energy and Environmental Design (LEED) is the Green Building rating system released by the US Green Building Council (USGBC) in 1998.

(6) Building Research Establishment Environmental Assessment Method (BREEAM) was the world's first environmental rating system that was released in the UK in 1990. (Bougdah & Sharples, 2010)

is concerned, in particular, the relationship between building information models and sustainable building designs standards.

Initially the research started with examining technology to support sustainable design, in the course of the work the vastness of scale became apparent, and after several incarnations of this work, the scope has been narrowed down to demonstrate a limited aspect of sustainable assessment and technological support. In particular, two representative credit samples over three versions of the Leadership in Energy and Environmental Design, New Construction (referred to as LEED in this dissertation) rating system has been used to demonstrate the approach. However, for reasons of historical accuracy of the work done throughout, I refer to both the broader scope of the technological investigations as well as to the more pertinent aspects of the current scope.

1.1 Background to the Research

The research described evolved with the development of two major projects: the Sustainable Building Information Modeling (SBIM) project with Autodesk® and Construction Operations Building Information Exchange (COBie) to LEED templates with the Construction Engineering Research Laboratory (CERL). Central goals of the two projects were sustainable building design pre assessments during the design phase of a project using LEED 2.1 version as the 'sustainable building rating system' (7). Both research projects sought to integrate design models with a sustainable building rating system to provide assessment of the buildings based on the selected rating system.

The motivation has been to find ways to organize informational requirement from the rating systems perspective and to integrate it with information from a building to assess the sustainability of the design. Both projects addressed the insufficiency of information related to sustainability assessments by investigating the informational needs and data structures that support design and assessment.

(7) 'Sustainable building rating systems' are defined as tools that examine the performance or expected performance of a 'whole building' and translate that examination into an overall assessment that allows for comparison against other buildings. (Fowler, 2007)

1.1.1 Research Scope

This dissertation started with the Autodesk project in 2006. The task was to determine the feasibility of 'Green BIM' across multiple sustainability ratings. In the course of doing this work, and testing for feasibility, it became clear that the task was way beyond the capabilities of any available BIM technology. The reasons for this are numerous; and relate to available data, data structures, information exchange standards, and sustainability ratings information formats etc. (Krishnamurti, Biswas, & Wang, 2010) Relevant findings and issues from the Autodesk research project are described in Chapter 3, Sections 3.2 and 3.4.1. In the context of the project, I originally planned to develop a framework to support sustainable design, concentrating on LEED NC 2.1 as the exemplar demonstrator rating system. Over the years, LEED has evolved through several versions, namely, 2.1, 2009, and currently, v4. With this evolution is a corresponding expansion of the scope of the original intent. To make the task more manageable, a representative credit from two main categories Water Efficiency, and Energy and Atmosphere are chosen to demonstrate the process.

The research now focuses on developing a general process, which provides support for sustainable building information requirement over evolving rating standards, with particular reference to two credits –Indoor Water Use Reduction, and Minimum Energy Performance across three LEED standards (versions 2.1, 2009 and v4). An expectation of this work still is in their utilization for sustainable design pre-assessment during design. In keeping with the original planned intent, the research background in Chapter 2 reviews building rating systems and their evolving nature; and Chapter 3 reviews the structure of the information for the basis to provide assessment support. The following section discusses a number of general areas in sustainable design, and assessment that this dissertation draws upon.

1.2 Sustainability

" Sustainable development is the kind of development that meets the needs of the present without compromising the ability of future generations to meet their own needs."
(Brundtland, 1987)

Sustainability has been subject to a multitude of interpretations; amongst these, the most widely known is the definition above given in the Bruntland Report. The Brundtland Report [(8)] identifies, among several issues, the limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs. This durable definition although flexible and open to interpretation, does not state ‘how to make sustainability operational’, that is, those things that ought to be done to ensure future needs of people such as basic needs for food, water, energy, resources and shelter. For buildings, terminology can be loose with words such as ‘green’ and ‘sustainable’ used interchangeably (Krygiel & Nies, 2008). Likewise, in this dissertation, these terms are used interchangeably.

1.2.1 Sustainable Building Design

“Sustainable design is a design philosophy that seeks to maximize the quality of the built environment, while minimizing or eliminating negative impacts to the natural environment.” (McLennan, 2004)

Sustainable design is a subset of sustainable development. As a prime consumer of natural resources, collectively, buildings heavily impact the physical environment (Bougdah & Sharples, 2010). Buildings account for a significant portion of greenhouse gas emissions. In the United States, buildings account for nearly half (46.7%) of CO_2 emissions, and nearly three-quarters (75.7%) of U.S electricity consumption (Architecture 2030 (a), 2012). With growing understanding and acknowledgement of the impact of buildings on environmental resources, the need for systems that can assess environmental performance become more important (Bougdah & Sharples, 2010). Green buildings [(9)], which address environmental issues, are becoming increasingly desirable, both as expressions of owner expectation and as design products.

Achieving a certain standard of sustainability as codified by a sustainable building rating system contributes readily towards reducing negative impacts on the environment; however, contemporary methods of achieving these goals require time and effort. One typically goes through different software and information sources in preparing and conducting assessment with respect to a chosen rating system (Figure 1-1).

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(8) Better known as *Our Common Future*, from the United Nations World Commission on Environment and Development, published in 1987.

(9) A green building is a structure that is environmentally responsible and resource-efficient throughout its life-cycle. (EPA (a), 2014)

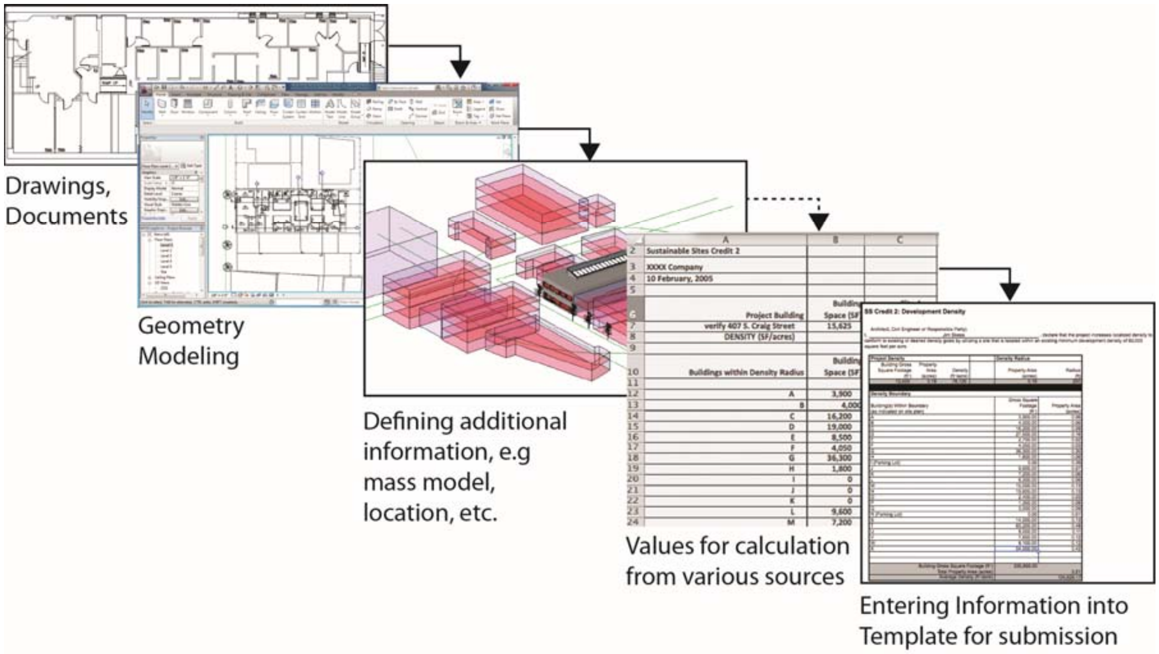

Figure 1-1 Typical information preparation from a design for assessment

The evaluation of a rating credit [10] requires a process of collecting and documenting information from various sources: design data, simulation results, maps, reference documents, and so on, which are, firstly, specified in different formats, and secondly, have enough semantic differences in the specification of conceptually similar entities. Design information in the form of CAD drawings, annotations, and documentation in text and spreadsheet formats cannot be readily used with sustainability rating tools; these have to be manually reconstructed, often, more than once, in order to satisfy assessment criteria. Processing sustainability related information engenders cost in terms of time and effort that could be a prohibitively high (LEED User, 2014). Such information is often manually defined in different domains as the undertaking of a cross-disciplinary design team. However, differing semantics across disparate disciplines, non-interoperable tools and datasets pose challenges to cross-disciplinary collaboration and could result in duplication of work (Huang, 2011).

At present rating systems are 'passive' (iiSBE, 2004) tools, used as checklists—that is, information from design software and other sources are accumulated and checked by the requirements and rules for each credit point. Integration of rating system information requirement

[10] Under the LEED 2.1 system, buildings are judged via a maximum of 69-point credit system in five categories of environmental performance and one additional area for innovative strategies. (USGBC (j), 2003)

and design information becomes essential for calculations throughout the design process (Simmons, 2010). Systems that demonstrate interoperability and information management for high performance building design are mostly designed with a combination of CAD and simulation tools.

Design professionals employ, or at any rate, reference a sustainable building rating system to evaluate building performance. This entails conforming to certain requirements, which in turn, engenders additional knowledge. Adequately coping with this necessitates developing effective computational environments to assist in decision-making. This is especially important in the early design stages where key decisions are made, which have important performance implications. Conducting environmental assessment during later construction stages is frustrating as any improvement to achieving a desired performance can be expensive as well as time consuming (Kibert, 2005). Currently, there is a lack of an effective solution owing to the amount of data needed to make an assessment, and the nature and number of performance criteria (Kasim, Li, & Rezgui, 2011).

1.2.2 Sustainable Design Assessment

"There are numerous environmental benefits as a result of LEED and other rating systems as compared to typical building construction. LEED certified buildings use a lower percentage of materials with high levels of toxicity, use less water and energy and have less negative impact on the physical landscape."
(Parr & Zaretsky, 2011)

Currently and commonly, buildings are deemed sustainable by certification (e.g., by reference to an authority such as LEED [11], BREEAM [12] or some appropriate equivalent system for assessing sustainable buildings) (Cole, 1999) (Gissen, 2003). That is, 'sustainability' in the building sector is codified by standards, which manifest themselves in the form of a 'sustainable' or 'green' building rating system. The basic aim of a building-rating system is to set criteria with which to rate a building and to provide a score for that rating. A green or sustainable building rating system is defined as a tool that examines the performance or expected performance of a 'whole building' and translates that into an overall assessment that allows for comparison with other buildings

(11) Leadership in Energy and Environmental Design (LEED) is a green building rating system developed by the US Green Building Council (USGBC) in 1998. The newest version LEEDv4 was released in 2013.

(12) Building Research Establishment Environmental Assessment Method (BREEAM), released in the UK in 1990, is the world's first environmental rating system for buildings (Bougdah & Sharples, 2010).

(Fowler, 2007) (Krygiel & Nies, 2008). To produce designs that fulfill a certain 'sustainability' rating require much more than designer assumptions or intuition (Aish, 2005). Assessments in general are "a multifaceted and multi-phase process" (Turkaslan-Bulbul, 2006), which ensures measures are taken for a building to achieve certain levels of performance in areas such as reduction in energy consumption, lowered carbon footprint, etc., in general, conservation of resources.

Rating systems for sustainable building design offer guidelines and means for comparing and benchmarking the performance of buildings with respect to 'green-ness' (Fowler, 2007). However, the nature of rating systems is such that the standards themselves are a moving target (Williams D. , 2007). Likewise, rating systems that gauge sustainability are in a state of flux; that is, the rapidity and complexity with which US Green Building Council's rating system LEED 2.1 transformed to LEED 2009 in 2009 and most recently in Fall 2013 to LEED v4 attests to this evolution in scope and detail.

In addressing a general process of sustainable design and assessments, there are some important aspects to note—information for sustainability assessments is gathered and accumulated from pre-design through building occupancy (Williams L. , 2010), as projects are required to register early in the design process to document project performance throughout (Solomon, 2005). See Figure 1-2.

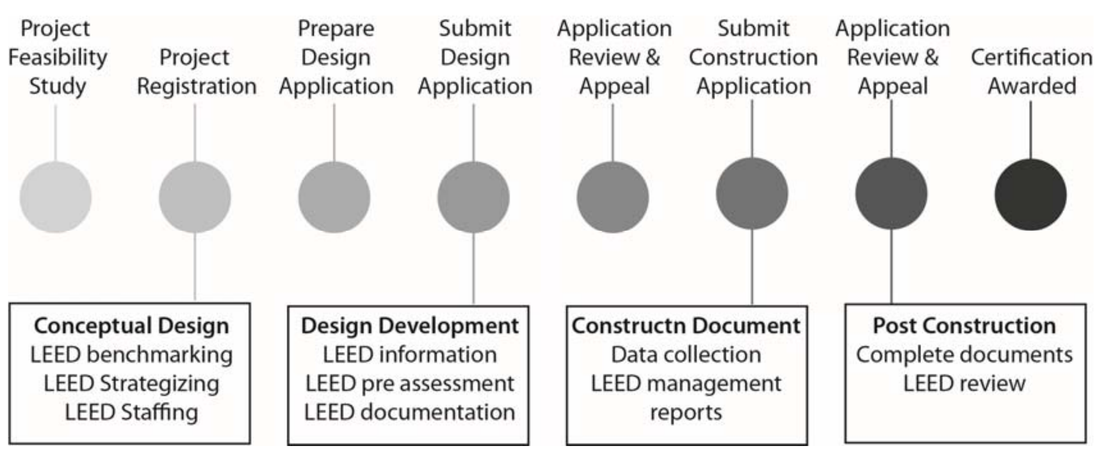

Figure 1-2 Typical information preparation for LEED certification

Throughout the process teams of professionals need to have access to information about a project. For example, site boundary and area information is required by an engineer to assess storm water management, and is required by the designer to assess site density and connectivity. When project information is made available to all parties, it is still a challenge to coordinate and manage the information, with consistency, throughout the life of the project.

In this dissertation the terms ‘assessment’ and ‘evaluation’ are interchangeably used to describe the method adopted to verify submittal information. Submittal is the final form in which information accumulated from the design and pre-assessment is prepared for LEED certification review. Submission documents are usually in the form of online templates, text documents, Excel sheets, and drawings. The challenges for sustainability assessments are multifold as sustainability, like design, is not static—it is changing, iteratively, based on evolving knowledge that connects science and design (Williams D. , 2007). Systems, which gauge sustainability, are periodically reviewed with changes and increasingly stringent requirements; currently, there is no comprehensive way to accommodate for rating system changes and corresponding information requirements within design software.

1.2.3 Integrating Sustainability Assessment with Building Design

“[A] Building Information Model is a digital representation of physical and functional characteristics of a facility; a shared knowledge resource for information about a facility forming.”
(Smith & Edgar, 2008)

Digital design technologies have become almost universally adopted as the predominant means of production in current architectural practice (Kotnik, 2010). The survey by Wu and Issa shows that in present-day green building design efforts in BIM solutions facilitate communication, information exchange and submission submittals (Wu & Issa, 2010).

There are multiple ways of targeting sustainability in buildings, for example, through a pragmatic approach and well-managed processes (Williams, 2010). To this end digital design technologies are almost universally adopted as the predominant means of production in current architectural practice (Kotnik, 2010). Design documentation, essentially based on paper and ink, is produced by a computer-aided design (CAD) application to create drawings, which are either physically printed or digitally reproduced, as a series of individual files with no inherent intelligence (Krygiel & Nies, 2008). More recently, Building Information Models (BIM)s have paved the way for developing, storing, and updating digital design data (Krygiel & Nies, 2008). The acronym BIM in this dissertation refers to the noun (building information model) and not the verb (building information modeling). Additionally, these digital design tools offer possibilities of utilizing data throughout the design process. Digital computation allows for querying, design, pre-evaluation of requirements, and the generation of required forms for final evaluation. In order to promote the practice of sustainability at a larger scale, digital technology available through commercial design tools should be utilized to a greater extent in order to alleviate costs of design, evaluation and submission.

Rating systems vary from within the country and across regions. Consequently, the process for evaluating sustainable designs begins by choosing an appropriate rating system. The next challenge is to extract and evaluate the information from the design according to the requirements of the rating system that is set out for the different aspects of a design: starting from inception, occupation, and ultimately, decommissioning of the design. This creates the need for multi-phase, multi-domain evaluation procedures and necessitates a repository for the information.

To create an integrative approach to supporting designs with sustainability requirements, it is essential that we can identify, and thus represent, building objects and their parameters whose informational needs are required in evaluating for sustainable design. For instance, computational methods for energy, lighting, and airflow analyses were established long before the emergence of building information models. At the time the research for this thesis began, it was likely that performance analyses tools will have been embedded in future versions of primary BIM tools (Eastman, Teicholz, Sacks, & Liston, 2008).

In general, assessment involves the following steps: (i) selecting a suitable rating system; (ii) collecting data from the design and other sources; (iii) analyzing categories where the design can meet requirements by pre-assessment; and lastly (iv) submitting information for evaluation. Preparation for certification submission involves large volumes of data aggregation and information accounting, which is, despite the best of intentions, often, a deterrent to designers and the design process (Cheatham, 2011). This research focuses on the first three steps—essential before any design can be submitted for certification.

1.2.4 BIM and Interoperability

"The implementation of Building Information Models, and the exchange of such models between tools, requires some form of data format specification."
(Huang, 2011)

Incompatible data formats of necessary information for sustainable design assessments are deterrents to making the process accessible to a wider design community. A study from the US

National Institute of Science and Technology (NIST) shows that around 30% of the construction cost is due to information inoperability problems (Gallaher, O'Connor, Dettbarn, & Gilday, 2004). According to the NIST study, interoperability relates to both the exchange and management of electronic information, where individuals and systems are able to identify and access information seamlessly, as well as comprehend and integrate information across multiple software systems. (Gallaher, O'Connor, Dettbarn, & Gilday, 2004) In the construction industry, inadequate interoperability prevents digital communications between software programs used by designers, contractors, specialty contractors, as well as building owners and operators. In the same study, in the architecture, engineering and construction (AEC) domain, the annual cost to stakeholders lost due to inadequate interoperability is estimated to be $15.82b. The $15.8 billion loss reflects costs incurred during both construction ($6.8 billion) and operations and maintenance ($9 billion). Figure 1-3 shows the breakdown of cost per stakeholder group in the building life cycle phase.

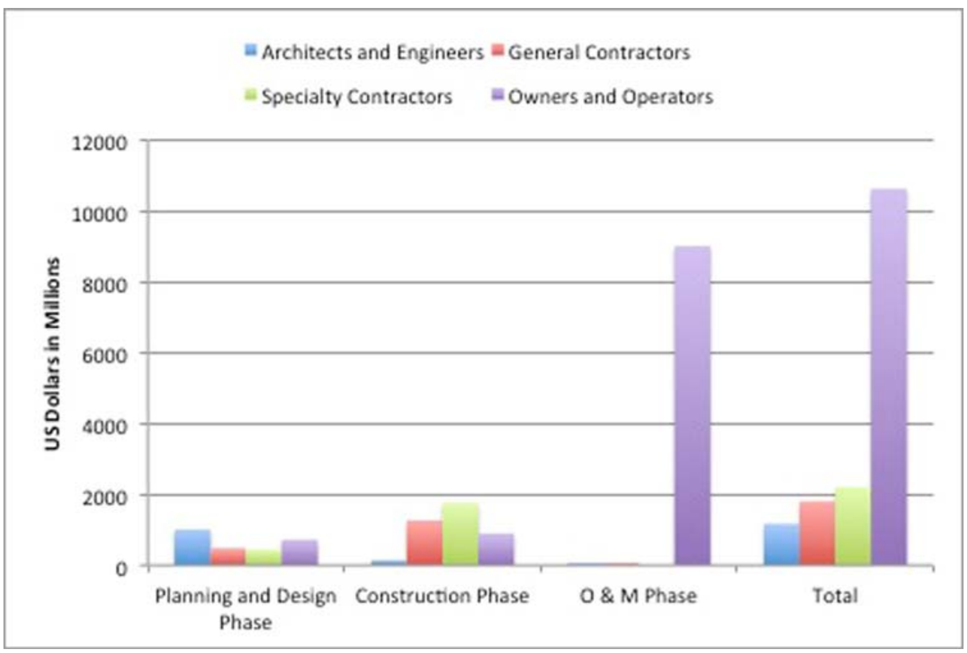

Figure 1-3 Cost of inadequate interoperability by stakeholder group in life cycle (Gallaher, O'Connor, Dettbarn, & Gilday, 2004)

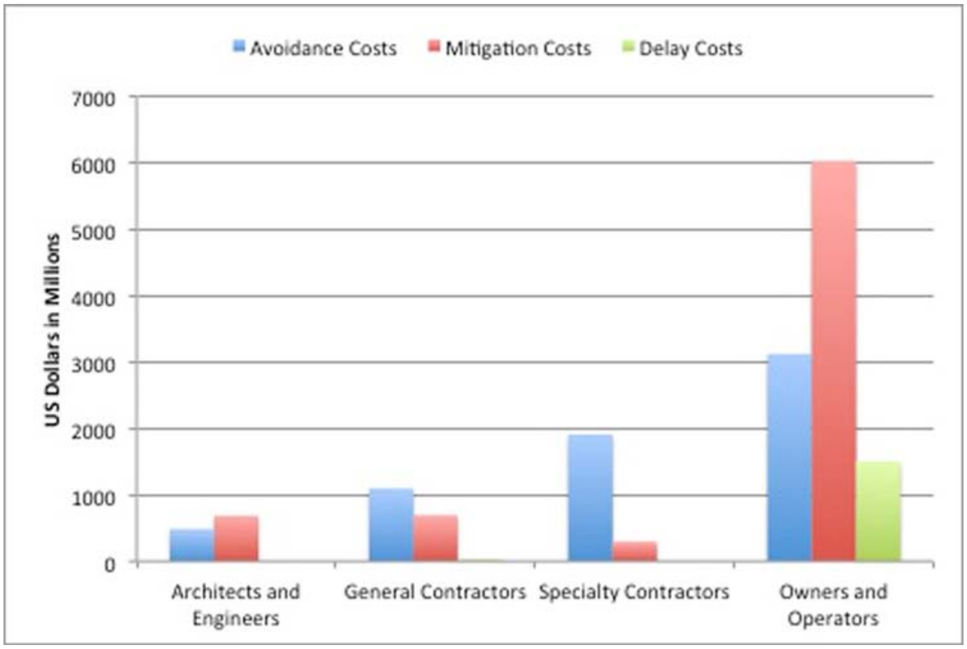

Figure 1-4 Cost of inadequate interoperability by stakeholder group and cost (Gallaher, O'Connor, Dettbarn, & Gilday, 2004)

The NIST study conveys that the construction industry has incurred significant expense associated with three kinds of interoperability costs: avoidance, mitigation, and delay. See Figure 1-4.

- Avoidance costs include redundant computer systems, inefficient business process management and redundant IT support staffing.
- Mitigation costs include manual reentry of data and request for information
- Delay costs include labor for idled employees

In 2002, when the study was done, the cost of non-residential public construction in place was estimated at 208,174 million (US Census Bureau (a), 2012). Under the assumption that the ratio of cost of interoperability and non-residential public construction in place remain the same, then the cost of interoperability can be estimated to be $19.7 billion in 2014 (US Census Bureau (b), 2014) without considering either inflation or changes in technology. (Figure 1-5)

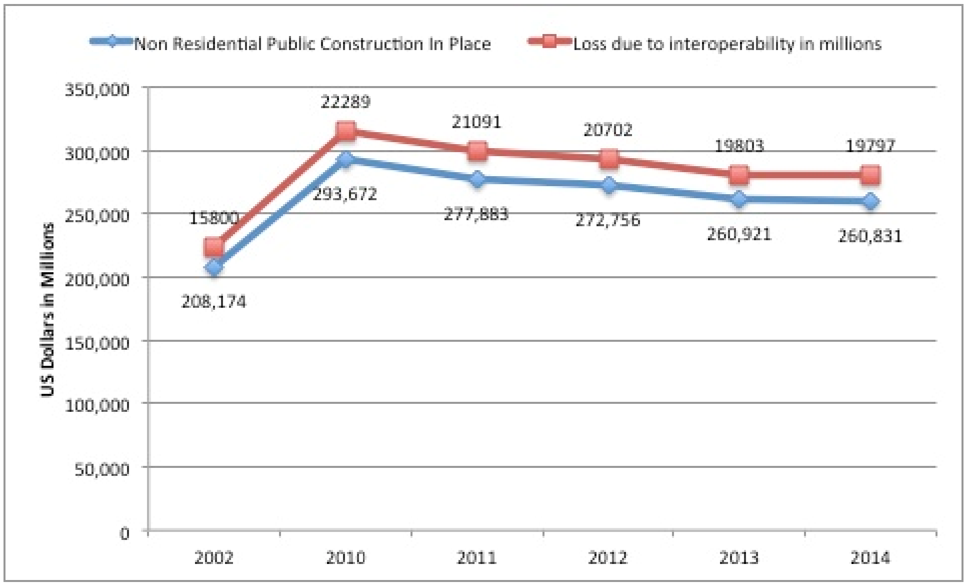

Figure 1-5 Projected Cost of inadequate interoperability in 2014

In principle, building information models represents the potential for interoperability by capturing, within a single model, all informational aspects of a building over its entire lifecycle. Typically, in the AEC domain, where possible, information is made available through open source data standards: for example, Industry Foundation Classes (IFC) (buildingSMART (a), 2010); ISO standards (ISO (a), 2013); XML standards, for example, IFCXML and gbXML (gbXML, 2014). An important pragmatic consideration in any consideration of data exchange format is the prevalence of adoption and implementation by stakeholders in the building industry. For instance, major commercial architectural CAD software vendors such as Autodesk®, Bentley®, Graphisoft®, and Vectorworks® all provide implementations of both IFC and gbXML models. However, no single standard that provides support for sustainability assessment completely suffices as a data structure.

Both IFC and gbXML formats are extensible and can potentially represent information for sustainability assessment (although gbXML was originally developed to capture information for energy analysis). To share design information and sustainability related information from a software tool, it is essential to have a data structure that can integrate necessary building information and evaluation requirements. To this end the Construction Operations Building Information Exchange (East B. , 2014), COBie format was explored as a suitable data structure for lightweight [13] building model information exchange to support sustainability assessment. COBie is based upon an IFC model that is free of geometry information. COBie information can be found in one of three formats: IFC STEP Physical File Format (IFC SPFF), ifcXML or SpreadsheetML (East B. , 2014). Although COBie data can be viewed in commonly used spreadsheet software, the focus of COBie is not on software products, but on strategy for moving building information through the project life cycle.

1.3 Problem

The following issues have been delineated based on the current state of support tools for arriving at sustainable building solutions. The issues are related to identifying and managing sustainability information, integrating design and sustainability information, and ultimately, satisfying qualities for a building to be deemed sustainable by a sustainable rating system.

Besides rating systems, there are other tools available to the modern designer. These include software design environments such as CAD or Building Information Modeling tools, augmented by a suite of simulation packages to analyse and verify aspects of performance. Typically, these are neither integrated to, nor provide guidance required to achieve sustainable design outcomes with, a particular software environment.

Sustainable design requires information about sustainability from conception of design through the whole lifecycle of the project; currently, information is fragmented across domains, not readily available to offer guidance to a designer or be accessible within a software-based design environment. A BIM structure acts as a data container to hold project information and provides placeholders for data not yet explicit in the model. However, current BIMs do not contain sufficient explicit data to handle all aspects of a rating system and require additional external data (to be accommodated in a cohesive manner). Available data exchange formats for interoperability and sustainability information management requires extensions and augmentation suitable for supporting sustainable design.

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(13) A lightweight building information model is one that contains minimum requirements for the transfer of construction project information. Translations between lightweight BIM formats such as spread sheets and the underlying open international IFC-based standards upon which COBie is now based on are provided by bimServices toolkit, which not part of the COBie standard. (National Institute of Building Sciences buildingSMART alliance™, 2012)

In adopting a rating system as a road map to sustainability, it is important to note that currently there is no comprehensive way of managing changing rating system requirements, nor a way for designers to update or change requirements that could be amenable to computation. This research focuses on LEED, with selected credits over the evolutionary period from version 2.1, 2009 and v4. It seeks to provide an approach to see if there is a pattern of information requirements that can be used for the next rating system version.

1.3.1 Research Questions

I consider three specific questions in this research. These are:

- *How can green building rating systems be used more efficiently to guide sustainable design?*

Following current processes, designers use requirements from a chosen green building rating system while working in the traditional paper based or CAD based system. However, information from drawings or model needs to be extracted for purposes of calculations; at some point this information has to be digitized, especially for energy simulations. The process requires a different approach for extracting, holding and managing such information.

- *How can green building assessment requirement be defined and managed so that it may lend itself to computation using available data exchange formats and structures?*

This last question seeks to respond to the first two.

- *Can a general process be developed so if one were to go forward in time, could information for sustainable building design be used in a sustainable manner- such that methods evolve with changing rating system requirements?*

Sustainable building rating systems only make sense if designers can use them. Maintaining currency of rating systems and working in conjunction with design environments becomes essential for designing sustainable buildings.

1.4 Research Objectives

The main research objective presented in this dissertation is to create a framework that supports sustainable design assessment by providing adequate information in the design process. Informational needs from a sustainability rating system perspective and information available from building information model using data exchange formats are used to develop a framework. This approach will:

1) Identify the informational ingredients and processes involved in sustainable building assessments for integration with a building information model;
2) Provide a process to use available building information and assess it according to rating system requirement translated into rules using suitable data structures; and
3) Offer a way to modify rating system rules as they change.

It is expected that an integrated process of assessing design and exploration by supporting case studies will demonstrate the usage of the proposed work within the context of sustainable design.

1.4.1 Integrating sustainability assessment information with design

To meet the first objective of *integrating sustainable building rating system requirements with a building information model*, a framework, which maps rating assessment requirements to a BIM, is developed with the assumption that the latter is well formed.

Data for assessing requirements comprise external, performance, BIM and building model related data. The list of assessment areas for each rating system is given in Chapter 2: Table 2-4. External data is not resident in the model, but is needed for various assessments. Examples include rainfall data, vegetation type and their evapotranspiration rates, water runoff coefficients for different ground cover types and such. Performance data are generated by specific analyses, which are uniformly data oriented, objective and, mostly, adhere to formal standards and guidelines such as ISO, ASTM, or ASHRAE (Trusty, 2000). The US Department of Energy Office of Energy Efficiency and Renewable Energy maintains an extensive directory of building software for generating performance related data, namely, tools for evaluating energy efficiency, renewable energy, and sustainability in buildings (US Department of Energy, 2011). Additionally, there are model related or dependent data, which are inherently integral to and augment the building information model. These include necessary BIM element [14] attributes that are not standard in any

[14] A BIM element notionally refers to entities (objects or attributes) ordinarily contained in a typical building information model. Examples of BIM elements include walls, doors, and floors etc., which have attributes such as area, volume and so on. For example, LEED credit SS 2, Development Density, requires different types of community buildings around the building being designed; these are *credit elements*. Elements in the model that represent 'community' buildings are BIM elements with appropriate attributes such as site area and building area.

building model such as occupancy data, custom attributes such as recycled content in material, plumbing fixture flow rates, and type of vegetation etc.

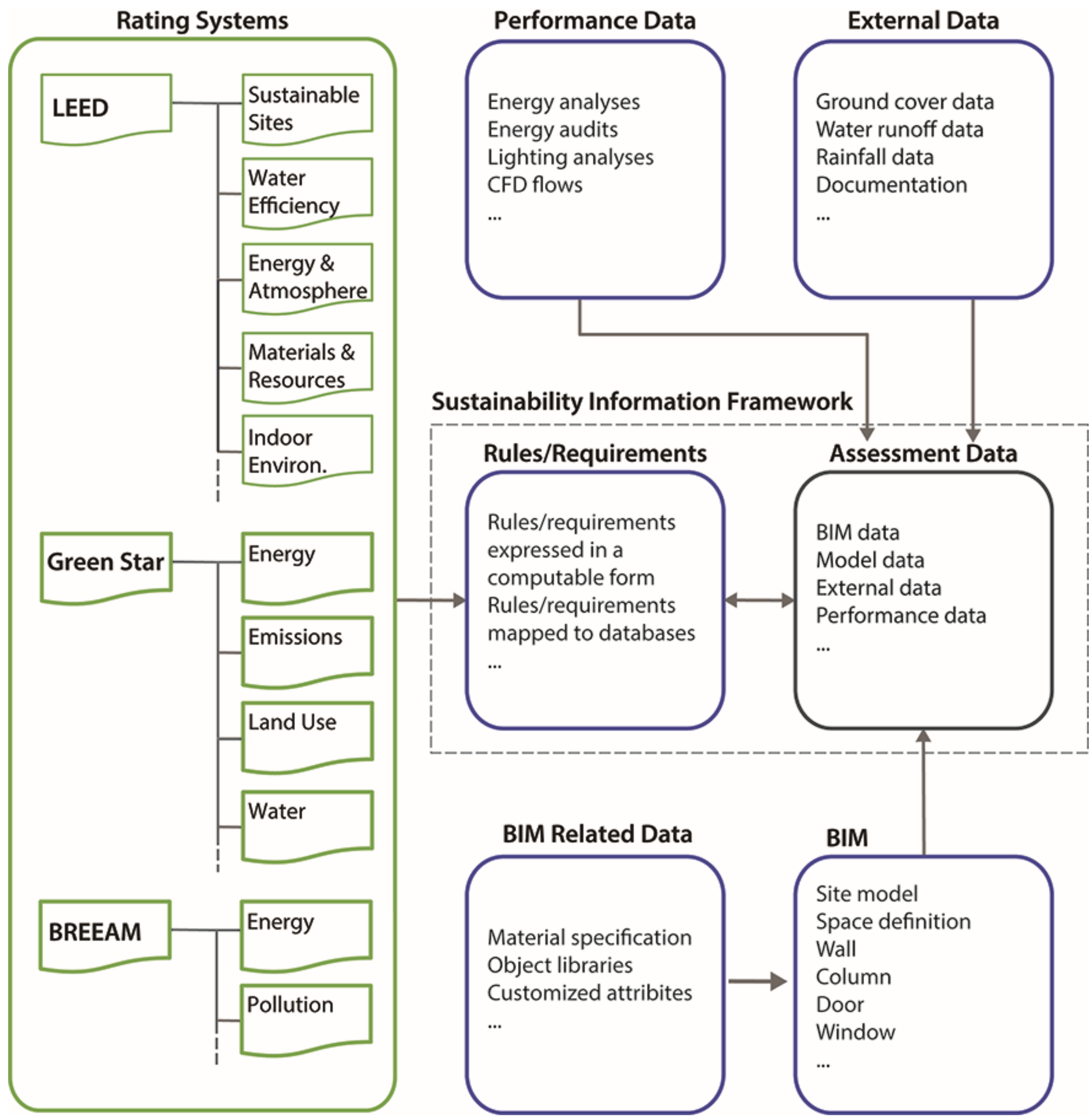

Figure 1-6 Sustainability information framework

Figure 1-6 illustrates a framework to support information flow between rating systems, sustainability assessment information, building model information, performance data as well as other pertinent data in externally distributed databases. As can be seen from the figure, rating systems are classified as semantic categories each relating to an aspect, such as site, energy, water use, indoor-air quality, etc. Each category relates to a number of distinct environmental impacts that can be measured, each of which assessed according to specific conditions or requirements. To evaluate these conditions there is a set of associated assessment data points that are derived from information contained in the building model or from performance analyses and other (external) sources.

Performance and external data can be quantitative or qualitative measures. Quantitative measures reflect numerical values for instance, annual energy use, water consumption, greenhouse gas emissions, volume of reused material and so on. Quantitative data can be measured, modeled or a combination of both (Todd & Fowler, 2010). On the other hand, qualitative measures employ comparative measurements such as the impact of ecological value (Nguyen & Gao, 2010), or rely on user confirmation that certain procedures have been followed. This process takes time and effort to input data, which vary in interpretation between different professionals (AlWaer, Sibley, & Lewis, 2008). Figure 1-6 is revisited in Chapter 3, Section 3.4.3.

To provide support for sustainability assessments, general types of information that needs to be handled are investigated. A grounded theory approach (Glaser & Strauss, 1967) is adopted to realize the informational needs for sustainable building assessment. This method was used in concert with the Autodesk sustainability team to create the initial structure for formulating the informational requirements. Grounded theory states that by following an iterative process of data collection, analyses and interpretation, information gets grounded into context and thus, leads to theory formation.

A representative list of categories and consequently subcategories have been formulated through exhaustive examination of data requirements from different rating systems and from case studies of building model information, mainly, for new construction commercial building types primarily focusing on requirements for the design phase, in detail, water use reduction and energy efficiency.

1.4.2 Framework for supporting sustainable design assessment

To meet the second objective of *providing support for sustainability assessment*, a prototype is developed, which demonstrates design assessment using the LEED NC 2.1 sustainable rating requirement, with chosen categories, on a design model with sufficient [(15)] information, and sharing

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(15) Here information is deemed sufficient if it represents a minimal set of requisite information for sustainable design assessment. In practical terms, this is exemplified by data elements that have been identified as being ‘required’ and ‘specified’ within the extended COBie data structure during the ‘Early Design Phase’. See Chapter 3 Section 3.4.2.

information across different disciplines and domains within the project team. Nominally, this consists of a geometry model with construction, material, location, and project information.

To integrate requirements between a rating system and a building information model, a mapping has to be established between credit elements [16] and BIM elements. However, not all requisite BIM elements are to be found in a building information model. There are two possible ways of specifying new BIM elements. Firstly, the definition of existing BIM entities (objects) can be extended; and secondly, new BIM entities can be defined. This necessitates augmenting the building information model by identifying additional BIM elements with the possibility of accommodating the required data in external databases.

1.4.3 Formalization of an information model for sustainable pre-assessment

The third objective acknowledges the fact the rating systems evolve periodically and fairly frequently. For example, in the United States, LEED 2.1 has led to LEED 2009, which, in turn, is superseded by LEED v4 in 2013. In the developed framework, updating rules of LEED version has been addressed in the Rules/Requirements module (Figure 1-6) through a flexible approach described in Section 4.2.2. In demonstrating a process for catering to rating system rule changes, it is evident that these rules apply to a wide range of building elements and processes, which makes it difficult to establish the right ingredients for a repository to develop general processes for assessment. In addition to the work done in developing the framework and prototype, another approach using a knowledge model was explored and experimented to provide an information model for sustainable pre assessment. To promote sustainable construction, and assist designers in decision-making, the construction industry needs to intensify its efforts to move to a knowledge intensive mode (Wetherill, Rezgui, Boddy, & Cooper, 2007). A way of addressing the information requirement is by creating an ontological model, a knowledge model, which is "designed to meet functional requirement of communication, representation and data exchange" (Gruber, 2003). To capture domain knowledge, this part of the research develops representations of concepts associated with building design, its components and information requirement for sustainability assessment to provide the user with a model that can be modified and updated as required.

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[16] A credit element is an entity that is required for the evaluation of a certain sustainability credit, for scoring a point towards certification. Once a credit element requirement has been mapped to BIM elements in the building information model, it can then be used in an assessment of the design.

1.5 Organization of the Dissertation

Chapter 1 Introduction: This chapter describes the context, the problem and the research objectives for developing a general framework supporting sustainable design information. The case for using building information with sustainable rating standards in an integrated design process is explained. Current concepts of sustainable design, terminology and current methods of sustainable design assessment are presented.

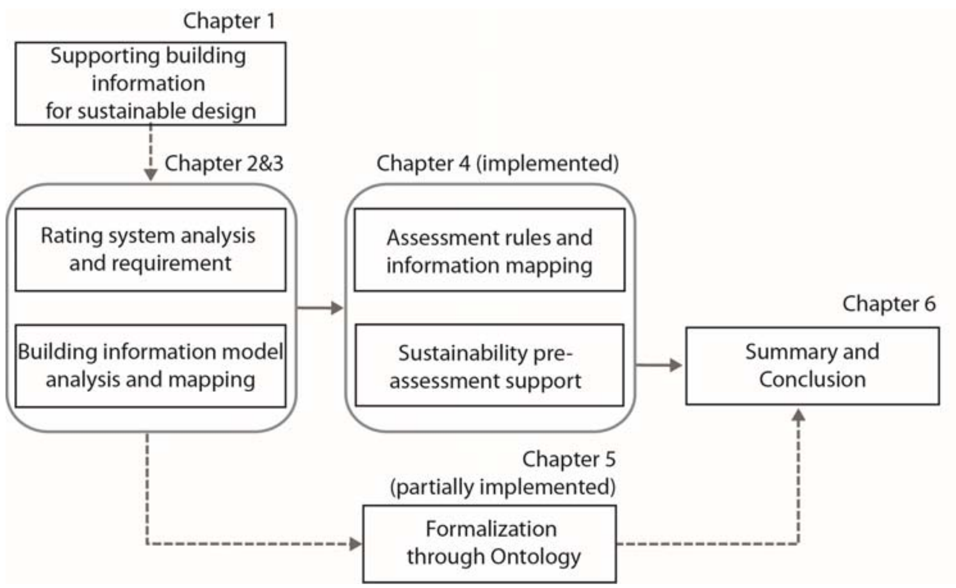


Figure 1-7 Chapter layout

Chapter 2 Background Review: Chapter 2 covers existing research and details of fundamental concepts crucial to the development of a general framework for sustainable design assessment. The current paradigms in undertaking evolving sustainability standards and the influences they have in designing processes for sustainable building assessment are described. An overview of different sustainable building rating standards that were used to gather information for a sustainability information database is given. Current sustainability assessment tools, software, and approaches are explained.

Chapter 3 Information Requirement for Pre-assessment: This chapter explains the process of formulating information requirement for pre-assessment. The comparison and analysis with current building information model information availability is discussed.

Chapter 4 Supporting Sustainability Pre-assessment Chapter 4 provides an implementation of a prototype under the proposed framework. It is the basis for demonstrating pre assessment for LEED NC 2.1 (4 major categories- sustainable site (SS), water efficiency (EA), materials and resources (MR), and energy and atmosphere (EA)), LEED NC 2009 (selected credits within WE and EA categories) and LEED v4 (selected credits within WE and EA categories) rating systems by formulating rules as computational.

Chapter 5 Formalization: Chapter 5 follows principles in knowledge design; an ontological approach is described from the context of sustainability assessments. The objective of this chapter is to describe the components of a proposed knowledge model, its mechanism and output for formalizing sustainability assessment related information as an additional option to information organization and management.

Chapter 6 Conclusion: The final chapter summarizes the work done in this research, its contributions and implications, and highlights important research issues yet to be resolved.

Chapter 2

Research Background

This chapter provides the context that sets out the need for a framework for sustainable building design assessment and design support. It lays out the essential aspects that such a framework needs to support – namely, evolving informational needs from rating systems, from technology and from design tools that support design processes. The background review begins with a brief overview of the modern sustainable design movement through contributing events, literature, technology and rating tools in the recent six decades (Figure 2-1).

The modern sustainable design movement began in the sixties and seventies with the publication of Rachel Carson's *Silent Spring* (1962) and Donella Meadows' *Limits to Growth* (1972). The subsequent decades witnessed the publication of Gro Harlem Brundtland's influential report, *Our Common Future* (1987), and William McDonough and Michael Braungart's influential treatise, *Cradle to Cradle* (2002). These books galvanized the greater environmental movement as people and organizations became conscious of our biological heritage and resources (McLennan, 2004). During this period of energy crisis the public's perception regarding energy conservation design was not yet positive—the sustainable design movement was then better known as energy conserving design. During the eighties in the US, due to the cheaper energy prices, proponents of the movement made slow progress. The Rio Earth Summit in nineties brought the visible decline of environmental health to the forefront again. As the building industry's reaction to being the contributor of environmental problems, leading practitioners, philosophers joined and wider issues such as energy, materials and resources and indoor air quality fell under the purview of the movement (McLennan, 2004). In 1993 the US Green Building Council (USGBC) was formed and the first LEED pilot program was launched in 1998 (USGBC (d), 2009).

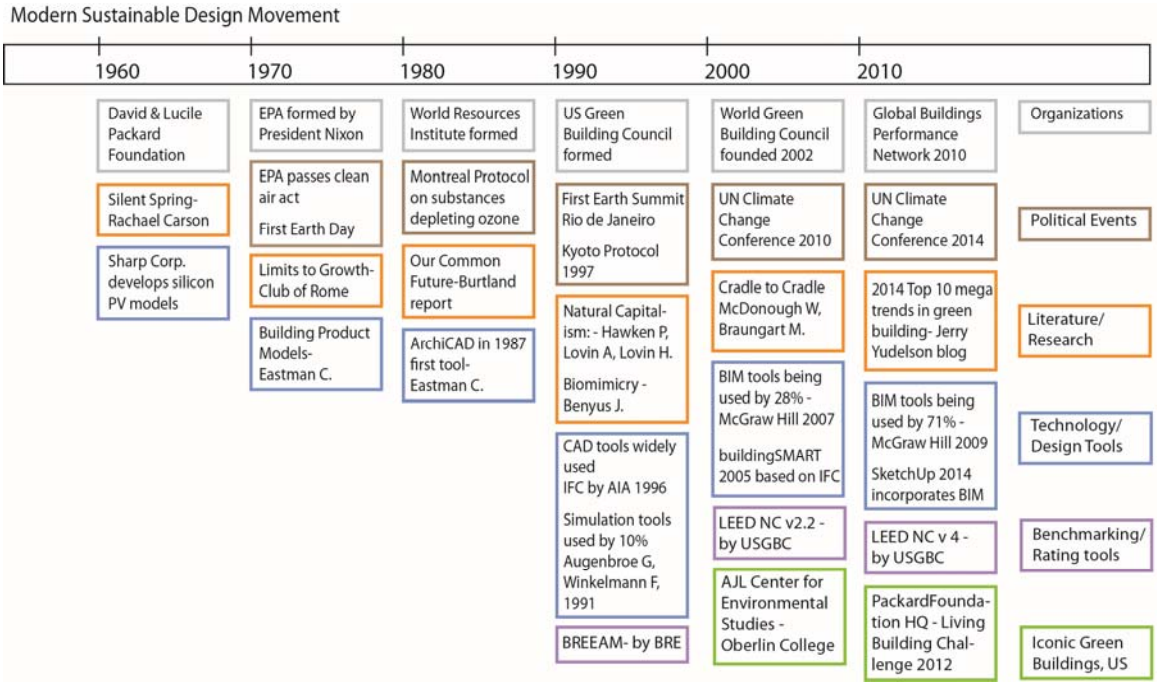


Figure 2-1 Chronology of organizations, publications, and events influencing sustainable building design

As seen in Figure 2-1, sustainable solutions, mostly, have come in incremental and small bites—integrated within millions of buildings in the form of energy efficient devices and systems, low CO_2 materials, smart choices for siting buildings, and so on all of which can be addressed by green design tools in an integrated cost-effective way (Kats, 2010).

Among the many areas of green design research, there has been considerable effort concentrated on green building rating systems (Kibert, 2008) (Ahn & Pearce, 2007). Tools that assist in sustainability assessment fall within the intersection of tools for design, performance and sustainability benchmarking. Figure 2-2 illustrates how tools can be part and parcel in implementing rating system requirements.

To successfully accomplish this vision, one needs tools that are accessible and easy to use. However, evaluations for sustainable design have not been captured to be designer accessible, for example, unlike model - or code checking where there are successful implementations. Much of the research on performance analysis and modeling tools focuses on energy-use (Huang, 2011).

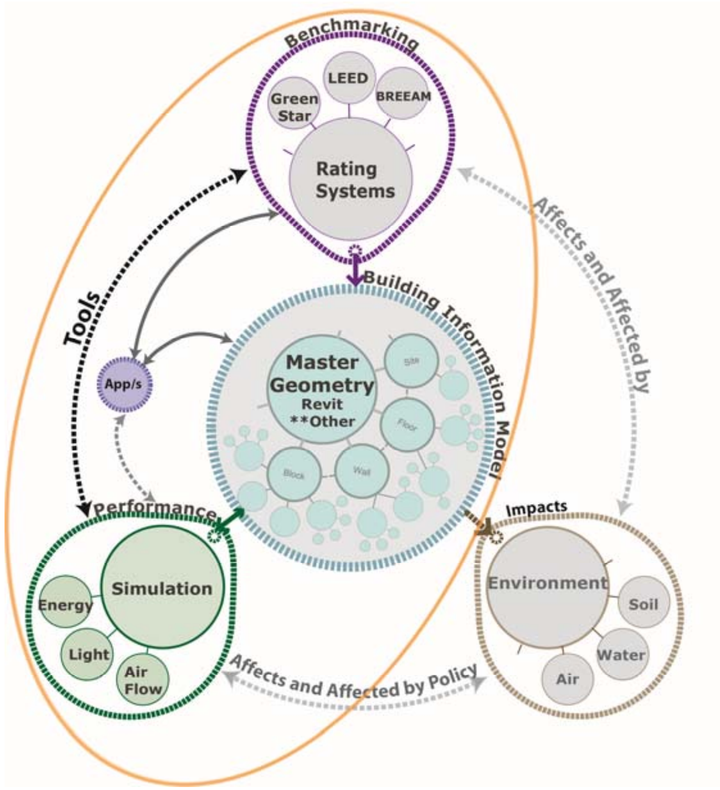


Figure 2-2 Sustainability assessment tools

The three sections that follow review sustainability as it pertains to the building domain through the use of sustainability rating standards in design, and the development and use of tools supporting sustainable design in the United States.

In Section 2.1, sustainable building design is reviewed in light of the impact of buildings on the environment and the role of sustainable building rating standards. A comparison of several sustainable building rating systems is presented in Section 2.1.2, which begins to identify the information required to address sustainability assessment.

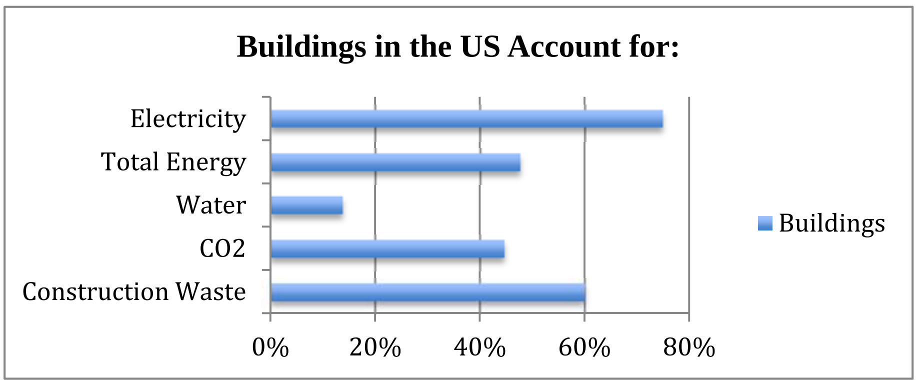
In Section 2.2, current sustainability assessment support tools are reviewed and an information exchange method for finding a possible approach to assisting sustainability assessment is described.

In Section 2.3, an approach to overcome the problem of formalizing information requirement for sustainability assessment is discussed.

2.1 Sustainable Building Design

"Sustainable design aims to reduce, or completely avoid, depletion of critical resources like energy, water, and raw materials; prevent environmental degradation caused by facilities and infrastructure throughout their life cycle..."
(WBDG, 2014)

Architecture presents unique challenges in the field of sustainability. Construction projects consume vast amounts of materials, produce tons of waste, and require lots of energy for heating and cooling. A summary of resource use by the building sector in the United States is given below in Figure 2-3.



* Data sources for the chart are given below

Figure 2-3 U.S. buildings resource uses

Energy and CO_2

- The building sector accounts for nearly half (46.7%) of CO_2 emissions in 2010, which is a significant portion of greenhouse gas emissions in the United States. By comparison, transportation accounts for a third (33.4%) of CO_2 emissions, and industry just under a fifth (19.9%). (Architecture 2030 (b), 2013)
- The building sector consumes nearly half (48.7%) of all energy produced and just over three quarters (75.7%) of all electricity produced in the United States. (Department of Energy (a), 2012)

Water

- Buildings consume 13.6% of all potable water, or 15 trillion gallons per year (U.S. Geological Survey, 2000).

Materials

- The EPA estimated that 170 Million tons of building-related construction and demolition (C&D) debris were generated in 2003, with approximately two-fifths (39%) and three-fifths (61%) from residential and nonresidential sources respectively (US Environmental Protection Agency, 2008).

According to Yudelson:

"Increased economic benefits are the prime driver of change for green buildings."
(Yudelson, 2008)

In the United States, a commercial building is now considered green if it has been certified by a commonly accepted standard of sustainability, for example, say, a LEED sustainable building design rating system (Yudelson, 2008). Initially, meeting requirements of green building programs, guidelines, standards or challenges was entirely voluntary, with rewards and recognition as the incentive (McLennan, 2004). In the United States alone, the LEED certification market has grown dramatically. The number of LEED certified projects has achieved a 103% average annual growth rate from 2000 to 2011 (Zhao & Lam, 2012). The GBIG research anthology summarizes over a decade of market experience and knowledge emerged from benefits and costs associated with high performance green building shows a reduction of energy and water use compared to conventional buildings (USGBC (l), 2014). The US General Services Administration (GSA) reports that the 12 earliest green federal buildings shows 26% less energy use, 19% lower operational costs, 36% lower CO2 emissions, and 27% higher occupant satisfaction (GSA (a), 2011).

Organizations such as the GSA which own or lease assets with nearly 354 million square feet (GSA, 2015), Environmental Protection Agency (EPA) and U.S Army now not only require minimum green building standards, but also mandate that future buildings be green (Athens, 2010). Adhering to a standard does not signal the end of a process; more positively, achieving a level of certification demonstrates that the project has fulfilled certain performance requirements set out by the standard. The following section outlines some of the more widely used sustainable building rating systems, and describes their informational needs required by a design team for sustainability assessments.

2.1.1 Sustainability Assessment Standards

There are many different building sustainability assessment systems that have been developed and used worldwide (Kats, 2010). Fowler and Rauch, in their study (Fowler, 2007), shorten this list by, firstly, combining several rating systems used in multiple countries, and secondly, subsuming those derived from other rating systems. Further criteria used in filtering the list such as maturity and dependability of systems, and the need to clearly communicate to multiple audiences, rating system results on various building types. Their review does not elaborate upon details of the technical basis and assumptions underlying each rating system, nor do they examine broader impacts on sustainability. A summary of three such representative assessments standards are given below showing changes in credits and points as their versions updated. The order that they are discussed is from the first launched system, BREEAM to the more recent Green Star. To identify informational requirements from a broader perspective, first the categories and the comprising credits are examined. Next, each of the credits is evaluated for the data that needs to be filled, the process of information organization and aggregation is discussed in Chapter 3.

BREEAM: Building Research Establishment's Environmental Assessment Method

The Building Research Establishment (BRE) was the first to develop an environmental impact assessment method, namely, BREEAM, the Building Research Establishment's Environmental Assessment Method (BREEAM (a), 2012). Subsequently, other countries adopted the BRE approach in developing their own assessment method (Reed, 2010). BREEAM has become the de facto measure of building environmental performance in Europe (BREEAM (a), 2012). There are versions specific to the United Kingdom; other versions are tailored for specific countries or regions, addressing specific environmental issues and weightings, construction methods and materials, and referencing local standards. In assessing a building, 'points' are awarded for each 'credit' or defined criterion. Points are then summed for a total score. The overall building performance is awarded a "Pass", "Good", "Very Good" or "Excellent" rating based on the score. BREEAM defines the following nine categories for assessing design and procurement: Management, Health and Wellbeing, Energy, Transport, Water, Materials, Land use and Ecology, Waste, Pollution and Innovation. Table 2-1 summarizes the categories, criteria assessed, the allocated credits and achievable points over BREEAM Offices 2008 issue 2.0 (released in 2008) and BREEAM Offices 2008 issue 4.1 (released 2012).

Table 2-1 BREEAM main categories

Category	Criteria assessed	2008 (Issue 2.0) Credit (Points)	2008 (Issue 4.1) Credit (Points)
Management	Commissioning, monitoring, waste recycling, pollution minimization, materials minimization	8(10)	5(10)
Health & Wellbeing	Adequate ventilation, humidification, lighting, thermal comfort	13(13)	13(13)
Energy	Sub-metering, energy efficiency and CO2 emissions	9(24)	9(24)
Transport	Emissions, alternate transport facilities	6(10)	6(10)
Water	Consumption reduction, metering, leak detection	4(6)	4(6)
Materials	Asbestos mitigation, recycling facilities, reuse of structures, facade or materials, use of crushed aggregate and sustainable timber	7(13)	7(12)
Land Use and Ecology	Previously used land, use of remediated contaminated land, Land with low ecological value or minimal change in value, maintaining major ecological systems on the land, minimization of biodiversity impacts	6(12)	6(10)
Waste	Construction Waste, Recycled aggregates, Recycling facilities	6(6)	6(6)
Pollution	Leak detection systems, on-site treatment, local or renewable energy sources, light pollution design, avoid use of ozone depleting and global warming substances	8(12)	8(12)
Innovation	Exemplary performance, BREEAM Accredited Professional, New technologies and building processes	N/A	10(10)

LEED: Leadership in Energy and Environmental Design

The United States Green Building Council (USGBC), which was founded in 1993, established the Leadership in Energy and Environmental Design (LEED) Green Building Rating System in 2000, with the most current being LEED version 4 released in Fall 2013 at USGBC's annual Green Build Conference. There are several LEED rating systems that are applicable respectively to new construction, existing buildings, commercial interiors, core and shell, schools, hospitals, hospitality, neighborhood, retail and homes. LEED takes an integrated design approach subsuming seven areas of performance assessment: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Air Quality, Innovations in Design and Regional Priority. Each area addresses specific environmental concerns (USGBC, 2014). A building is awarded points based on the number of goals it meets. Within each LEED category there are specific design goals that have to be met for any particular level of certification, which are, in increasing order of points: certified, silver, gold and platinum. In LEED version 2.1 each credit is worth a point, except for the Energy and Atmosphere category where multiple points may be awarded to a credit. In LEED 2009 and LEED v4, point distribution to credits vary, points are attributed to achieve single or multiple points. The final certification is based on the total number of points achieved. Table 2-2 summarizes the credits in each category.

Table 2-2 LEED main categories

Category	**Criteria assessed**	**LEED 2.1 Credit (Points)**	**LEED 2009 Credit (Points)**	**LEED v4 Credit (Points)**
Sustainable Sites	Construction related pollution prevention, site development impacts, transportation alternatives, storm water management, heat island effect, and light pollution	14 (14)	14 (26)	6(10)
Water Efficiency	Landscaping water use reduction, **indoor water use reduction**, and wastewater strategies	5 (5)	4 (10)	7(11)
Energy and Atmosphere	Commissioning, **whole building energy performance** optimization, refrigerant management, renewable energy use, and measurement and verification	6 (17)	6 (35)	11(33)
Materials and Resources	Recycling collection locations, building reuse, construction waste management, and the purchase of regionally manufactured materials, salvaged materials, and sustainably forested wood products	13 (13)	14 (14)	7(13)

Category	Criteria assessed	LEED 2.1 Credit (Points)	LEED 2009 Credit (Points)	LEED v4 Credit (Points)
Indoor Environmental Quality	Environmental tobacco smoke control, outdoor delivery monitoring, increased ventilation, construction indoor air quality, use low emitting materials, source control, and controllability of thermal and lighting systems	15 (15)	15 (15)	11(16)
Regional Priority		NA	4 (4)	4(4)
Innovation and Design Process	LEED® accredited professional, and innovative strategies for sustainable design	5 (5)	6 (6)	6(6)
Location and Transport	Site and neighborhood, development impacts, transportation alternatives	NA	NA	*8(16)

* Previously, Location and Transportation used to be part of the Sustainable Sites category

The credits chosen to focus information requirements and process for assessment are taken from Water Efficiency and Energy and Atmosphere categories. The EA category was selected as it has the highest possible points (35 out of 110) among the categories and without fulfilling the prerequisite Minimum Energy Performance further credits cannot be attempted. This is known as EAp2 in LEED 2.1, EAp2 in LEED 2009 and EA103 in LEED v4. One of the potential cost savings for green buildings is operation cost reduction by using less energy. In the Water Efficiency category the Indoor Water Use Reduction credit known as (WEc3 in LEED 2.1, WEp1 in LEED 2009 and WE102 in LEED v4) is selected as another sample credit to test over the three versions of LEED. The Indoor water use reduction credit's intent is to maximize water efficiency within buildings to reduce the burden on municipal and wastewater systems. It calculates a minimum 20% water use reduction from the baseline (not including irrigation). The Energy and Atmosphere (EA) section in LEED 2009 uses energy cost savings, rather than actual energy consumption savings as the prerequisite (at least 10% improvement from baseline) and the point calculation method. Upon analyzing the information requirements for credits, which is discussed in Chapter 3, Section 3.3, and Chapter 4, Section 4.3, the respective credits represented the elements that were being used more frequently by several ratings systems.

The credit and point distribution in Table 2-3 shows that with the exception of WEc3, all the other credits are prerequisites and have to be fulfilled. The prerequisites do not contribute to points themselves.

Table 2-3 LEED selected categories

Category	Criteria assessed	LEED 2.1 Credit (Points)	LEED 2009 Credit (Points)	LEED v4 Credit (Points)
Water Efficiency	Indoor water use reduction	WEc3: 1 (1)	WEp1: Prerequisite	WE102: Prerequisite
Energy and Atmosphere	Minimum energy performance	EAp2: Prerequisite	EAp2: Prerequisite	EA103: Prerequisite

GREEN STAR

"Green Star is a comprehensive, national, voluntary environmental rating system that evaluates the environmental design and construction of buildings and communities"
(GBCA (a), 2014).

Green Star was launched in 2002 by the Green Building Council Australia, a not-for-profit organization that encourages the adoption of green building practices (GBCA (b), 2014). It is, uniquely, supported by both industry and governments across the country. Green Star is built upon existing rating systems and tools such as BREEAM and LEED. Green Star has nine assessment categories. These are shown in Table 2-4.

Table 2-4 Green Star (Office Design_v2_2012) main categories

Category	Criteria assessed	Version 2 Credit (Points)	Version 3 Credit (Points)
Management	Commissioning (pre-post), building tuning, environmental and waste management	7 (12)	7 (12)
Indoor Environmental Quality	Ventilation rates, carbon dioxide monitoring, day lighting and views, thermal comfort and control, VOCs, noise, mold prevention.	16 (27)	16 (27)
Energy	Reduce energy and CO_2 emissions, sub-metering, reduce peak energy demand	7 (25)	5 (29)

Category	Criteria assessed	Version 2 Credit (Points)	Version 3 Credit (Points)
Transport	Small car parking, cyclist and public transport facilities	4 (11)	4 (11)
Water	Consumption reduction, metering, cooling tower and fire system water consumption	5 (12)	5 (12)
Materials	Recycling and reuse of structures, facade or materials, responsible use of steel and timber	8 (25)	10 (25)
Land Use and Ecology	Ecological value of site, reused land, reclaimed and contaminated land, topsoil and fill	5 (8)	4 (8)
Emissions	Refrigerant (GWP, leak detection, recovery), watercourse pollution (reduction in storm-water and sewer), Legionella prevention	9 (17)	8 (19)
Innovations	Exceeds Green Star benchmarks and scopes, innovative technologies and strategies	3 (5)	3 (5)

In general, sustainable building rating systems help to objectively align project goals to sustainability requirements. Whether it is meeting minimum criteria for certification, or in pursuit of making a positive contribution to the environment, there is a need to have standards that can be referenced for comparison. Different rating systems may (or may appear to) relate similar categories of assessment, but they can be very different in their intent, criteria, emphasis and implementation (Glavinich, 2008) (Kats, 2010) (AlWaer, Sibley, & Lewis, 2008). The manner and means by which the assessment categories are weighted, scaled and quantified in the various systems differ, and as such the same building may have two different ratings when judged according to two different rating systems. Actual ecological impacts of rating systems have not been scrutinized; however, this pertains to an avenue of inquiry that is beyond the scope of this dissertation.

2.1.2 Comparison of Selected Sustainable Rating Systems

In the rapidly evolving field of building environmental research and practice, various professionals have different agendas and requirements. This inevitably creates different expectations of an assessment tool. By evaluating the similarities and differences between sustainable design practices, better sustainable design guidelines and practices can be developed and used universally (Bunz, Henze, & Tiller, 2006).

Fowler and Rauch (2006) evaluate five sustainable building rating systems from a select group—namely, BREEAM (Building Research Establishment's Environmental Assessment Method), CASBEE (Comprehensive Assessment System for Building Environmental Efficiency), GBTool, Green Globes™ U.S. and LEED, which were considered for use in US General Services Administration (GSA) projects. The GSA determines the rating system appropriate for their projects based on the following criteria:

1) A system that is applicable to the large scale and complexity of federal building projects;
2) A stable rating system such that the evaluation of building performance is not subject to drastic change; and
3) A system, which tracks quantifiable achievements in sustainable design and is third party verified by a qualified assessor.

In addition to the analysis done by Fowler in selecting the five rating system, two other rating systems, HK BEAM, and Deutsche Gesellschaft fur Nachalltiges Bauen (DNGB) were added to cover the general scope of assessment areas from among across continents (America, Europe, Asia and Australia). The seven systems were chosen based on their levels of acceptance in the market, their differences in objectives, and a desire to provide an indication of the range of systems available. The systems chosen have distinguished themselves by developing unique approaches to the difficult challenge of quantifying sustainability. Table 2-5 illustrates how various sustainability-related categories are organized, and specifies the kind of (qualitative and quantitative) [(17)] information required by each in their main categories. The table is organized according to general assessment areas, which were assembled after reviewing the seven rating systems for the New Construction type of building. The general assessment categoryies, which the information is grouped, are listed in the leftmost column.

Each rating system differs in classification, importance, methods of calculation and verification. A generalization of the categories shows that most sustainable rating systems consider

[(17)] Quantitative measures reflect numerical values: for instance, annual energy use, water consumption, greenhouse gas emissions, volume of reused material etc. Quantitative data is measured, modeled or a combination (Todd & Fowler, 2010). Qualitative measures employ comparative measurements such as the impact of ecological value (Nguyen & Gao, 2010, or rely on user confirmation that certain procedures have been followed. This process takes time and effort, and can vary on the interpretation between different professionals (Al Waer, Sibley, & Lewis, 2008).

site, water use, energy use, materials and resource use, and indoor air quality as the main categories by which to measure environmental impacts (Kats, 2010).

However, there are other observations, which also can be gleaned from Table 2-5.

Table 2-5 Comparison of main categories in green building rating systems

	North America		Europe		Asia		Australia
Assessment Area	**LEED NC 2009**	**Green Globes**	**BREEAM**	**DGNB**	**HK Beam**	**CASBEE**	**Green Star**
1 Management			Management				Management
2 Energy and Atmosphere	Energy and Atmosphere	Energy and Resource Consumption	Energy	Technical Quality	Energy use	Energy	Energy
3 Emissions to the environment	Region specific environmental priority	Environmental Loadings	Pollution			Off-site Environment	Emissions
4 Sites	Sustainable sites (*Alternate transport*)	Site Selection	Land use	Quality of Location	Site Aspects (*Local transport*)	Outdoor Environment/ site	Land use
5 Transport			Transport				Transport
6 Water Efficiency	Water Efficiency	Water	Water		Water Use		Water
7 Indoor Air Quality	Indoor Air Quality	Indoor Environmental Quality	Health and Well-being		Indoor Environmental Quality	Indoor Environment	IEQ
8 Quality of Service		Service Quality		Quality of Process		Quality of Service	
9 Materials and Resources	Materials and Resources		Materials		Material Aspects	Resources and Materials and *Water Conservation*	Materials
10 Innovations	Innovations				Innovations		Innovations
11 Ecology			Ecology	Ecological Quality (Water)			
12 Economic Benefit		Economic Aspects		Economical Quality			
13 Culture and Heritage		Cultural and Perceptual Aspects		Socio-Cultural and Functional Quality			

For example, consider the assessment area: Water Efficiency. In CASBEE, the Comprehensive Assessment System for Built Environment Efficiency, it is called 'Water Conservation' and is a part of its Materials and Resources category (CASBEE 2012); in DGNB, water use is accounted for in Ecological Quality (DGNB 2012).

Likewise, the assessment area Transport is accounted for as 'Alternate Transportation' under the LEED 2009 Sustainable Sites category, whereas in DGNB it is considered as 'Public Access' under the Socio-cultural and Functional Quality category. In LEEDv4 'Transportation' has become a separate category named 'Location and Transportation'.

Table 2-5 clearly illustrates the difficulty in trying to uniformly classify sustainability related information. Categories have sub-categories or individual 'credits'/achievable points, which contain rules that determine acceptable thresholds for, say, site, material and water use; expected energy efficiency and indoor environmental quality in varying degrees without causing discomfort to the users of the space. By understanding the informational needs of different rating systems one can determine how they can be organized to support sustainable building design.

In summary, adopting a rating system, as a reference, is increasingly becoming part of design practice. Recent studies show an increasing commitment to incorporating 'green' features in building projects— the green market in 2005, was 2% of non-residential constructions; rose to 10-12% in 2008; and estimated to be 20-25% in 2013 (McGraw Hill Construction (a), 2012). There are increasingly more projects registered for LEED certification (Parr & Zaretsky, 2011). On the other hand, the 2012 Turner Construction barometer found a continuing decline in companies seeking LEED certification for their green buildings.

"Only 48% of executives said it is extremely or very likely that their company would seek LEED certification for a Green construction or renovation project. That's down from 54% in the 2010 survey and 61% in the 2008 survey."
(Turner Construction, 2014)

Some reasons for this trend are the following:

1. Cost, time and difficulty of the LEED certification process

The survey attributes 82% to the cost of the certification, 79% attributed to staff time required and 74% by the perceived difficulty of the process (Turner Construction, 2014). Regarding the cost premium incurred for green buildings, Kats (2010) states that “LEED certification does, but green design need not” (Kats, 2010).

2. Cost of LEED documentation.

The LEED submission process often requires significant amount of time and cost for the documentation. Currently, Green Building Certification Institute (GBCI) handles LEED project submissions and certifications. An online system – LEED Online has been established for the LEED 2009 NC to receive project registration and submission (GBCI, 2014). The LEED Online system is a useful tool, but the amount of effort to fill in the online forms is considerable. Research shows that the cost of LEED documentation ranges from $25,000 to $90,000, depending on complexity of project, team experience and level of certification (Yudelson, 2008) (USGBC (g), 2014). In many building projects, this may be the second biggest cost for the entire LEED certification process (Building Green, 2010).

3. Keeping up with rating system change is a challenge

This is true even for the more experienced designers. Often, there are not enough incentives within non-government organizations to support the needed ‘learning curve’ (Choi, 2009). The lack of team experience can also be an obstacle for LEED certification (Yudelson, 2008). Special training and guidance need to be provided.

2.2 Sustainable Design Decision Support Tools

“[A decision support tool] informs the decision making process by helping actors understand the consequences of different choices”
(iiSBE, 2004)

Tools that are available to help designers in the design stage towards sustainable design outcome decisions are categorized in many different ways (USGBC (k), 2014). The Annex 31 Study (iiSBE, 2004) describes two broad categories: *interactive software* or *passive*. Energy, lighting, and ventilation simulation and life cycle assessment tools for buildings are classed as ‘interactive’ whereas rating systems, environmental guidelines and checklists for design and management of buildings, environmental products and declarations are deemed ‘passive’. Interactive tools mentioned in the table are based on computer models and databases that employ user interfaces to increase interaction between the user and model. (iiSBE, 2004) Passive tools support decisions without much interaction with the user, and typically lack the degree of customization and computer support provided by simulation models. (iiSBE, 2004) Example of tools by classification is shown in Table 2-6 and Table 2-7. Tools used in the interactive category have varying degrees of integration with building design software, which can provide support to some aspects of sustainable assessments. While passive tools tend to contribute static information to the design process, they still lack the degree of customization and computer support. Making rating system requirements such as LEED available to a designer as an interactive tool would provide additional support in the design process. A combination of these tools is used to achieve LEED certification (Ahn & Pearce, 2007) (USGBC (c), 2014).

Table 2-6 Interactive tools for sustainable design adapted from (iiSBE, 2004)

Interactive Tools	**Examples**
Energy Simulation	EnergyPlus (EERE, 2013), Hour Analysis Program (HAP) (Carrier, 2014), Target Finder (Energy Star (b), 2014), Trace 700 (Trane, 2014)
Lighting Simulation	Radiance (Radsite, 2013), Daysim (Daysim, 2014), Ecotect (Autodesk, 2014)
Ventilation Modeling	Design Builder CFD (Design Builder, 2014)
Life Cycle Assessment	Athena® Impact Estimator for Buildings, Building for Environmental and Economic Sustainability (BEES) (Athena, 2014)

Table 2-7 Passive tools for sustainable design adapted from (iiSBE, 2004)

Passive Tools	**Examples**
Rating Systems	LEED, BREEAM, Green Star
Environmental Guidelines	ASTM E1903-97 Standard Guide for Environmental Site Assessments (ASTME International, 2014)
Checklists for Design and Management	LEED, BREEAM checklists, Sustainable Buildings Assessment and Compliance Tool (US Department of Interior, 2009)
Environmental Products and Declarations	Draft Guidelines for Product Environmental Performance Standards and Ecolabels for Voluntary Use in Federal Procurement, (EPA (b), 2014)

Between 2011 and 2013 the number of LEED certified buildings has doubled according to the USGBC (USGBC (k), 2014). In response to the steady growth, the US Green Building Council has released several apps, which manage and standardize documents for viewing and submission, such as CodeGreen and GreengradeLEED (USGBC (g), 2014). Recently, Autodesk® released tools to integrate LEED credit management with their building information modeling software (USGBC (c), 2014). A sizeable number of LEED credits require energy simulations; there are multiple tools, which offer support in this regard. For instance, Bentley's "AECOsim Compliance Manager" can "streamline the LEED certification process and maximize LEED credits" in the design stage (Bentley, 2014). The "COMNET Energy Modeling Portal for LEED Online" was developed to support eQUEST energy simulation results for LEED Energy and Atmosphere category (COMNET, 2014). Although effective in supporting LEED energy performance data, the tool does not supply all the requisite information for LEED EA Prerequisite 2 and Credit 1; there is external information, which has to be manually entered, in order to complete the LEED submission template. Tools for other aspects of LEED certification include "IES VE-Toolkit for LEED," which calculates LEED points for Indoor Environment Quality (IEQ) Credit 8.1 day lighting performance, IEQ Credit 7.1 comfort criteria, Water Efficiency Prerequisite 1-3, and EA Credit 2 and 6 for renewable energy (IES, 2014). These tools help facilitate the LEED certification process. However, LEED assessment and document management functions that are supported rely on proprietary software for energy modeling and building information. There is a need for tools and methods, which takes into consideration open source building information— proprietary and non-proprietary—in conjunction with sustainability requirements albeit for pre-certification assessment or managing building operations.

2.3 Integrated Approaches in Sustainable Building Assessment

"No single computer application can support all of the tasks associated with building design" (Eastman, Teicholz, Sacks, & Liston, 2008)

Among current tools BIM provide a repository of information, which is available for sustainable building assessments. However, not all information is directly accessible from (or even defined within) a single building information model. Data needs to be exported to another application or imported from an external data source (Krygiel & Nies, 2008). In this dissertation, building information modeling is examined in the context of green certification through the lenses of data requirement and extraction, suitable data structures for augmentation, tools and processes.

Recent research combining both commercial BIM and LEED requirements has demonstrated feasibility for semi-automated evaluation (Barnes & Castro-Lacouture, 2009) (Krishnamurti, Biswas, & Wang, 2013) Barnes and Castro-Lacouture based their research on Revit Architecture, and augmented Revit families with the necessary parameters. Any needed additional information needed was supplied. In our project we augmented Revit Architecture in two ways: firstly, by implementing a sustainability module that using plugin technology; secondly, by providing externally accessible databases (some salvaged and/or certified) for certain required information to support sustainability assessment. In both these studies, the additional required information for sustainability evaluation were added in two ways: by linking to external databases, or by augmenting the building model using the built-in capabilities of the proprietary BIM software to define and store additional information. The use of proprietary BIM software enabled us to demonstrate the feasibility of augmenting and evaluating information for a specific purpose, although, such support was limited to the particular proprietary BIM software and not readily generalizable to other BIM software.

2.3.1 Building Information Models and Information Exchange

Two recent surveys by McGraw Hill Construction (2009, 2012) show that the use of BIMs have risen to 28% in 2007, 48% in 2009 and 71% in 2012 in building design firms in the United States. (See Table 2-8) Moreover, now, for the first time, more contractors (74%) are using BIM than architects (70%) (McGraw Hill Construction (c), 2012).

Table 2-8 Adoption of BIM 2007 versus 2009 (McGraw Hill Construction (b), 2012)

BIM users	2007	2009	2012
BIM use in all respondents	28%	48%	71%
BIM use in contractor	13%	50%	74%
BIM use in architects	-	60%	70%

There are five reasons that can be attributed for the increasing adoption of BIM:

1. Less time needed for manual data re-entry
2. Facility to handle client requirements

3. Improved communication between stakeholders
4. Ease of design modification
5. Other cost reduction opportunities

One study (McGraw Hill Construction (b), 2012) shows that, for green building projects in particular, the impact of BIM is limited; among the respondents, one in ten have used BIM for LEED platinum projects. The other study (McGraw Hill Construction (b), 2012) provides a frequency index – namely, how often BIM is used in a process; in the area of sustainability rating and code analysis, although users see value, few use building information models. Figure 2-4

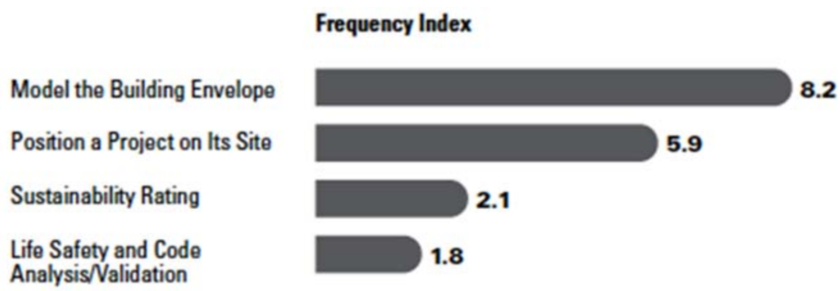


Figure 2-4 BIM user ratings for base building design activities (McGraw Hill Construction (b) 2012)

In summary, to better employ BIM, respondents of the study cited the need for:

- An integrated design process
- More energy modeling capabilities

  Broader application of the technology to assist owners and facility managers in the operation and management of buildings

Data Exchange

"There are significant differences between the IFC and gbXML schemas, including comprehensiveness, efficiency, robustness, redundancies, and portability ... In terms of comprehensiveness, both formats are not yet able to represent all information across all building performance domains."
(Huang, 2011)

An important and pragmatic consideration in any discussion on data exchange formats is the preponderance of adoption and implementation by stakeholders. In the Architecture Engineering

Construction and Management (AECM) domain, relevant information is generally available in a variety of open source data standards (Eastman, Teicholz, Sacks, & Liston, 2008), for instance, Industry Foundation Classes (IFC); ISO standards; XML standards such as IFCXML and gbXML; BIM templates; and COBie, the Construction Operations Building Information Exchange. According to BuildingSMART [(18)], these BIM efforts will integrate standards used in the AECM industry (buildingSMART (b), 2014). Major commercial architectural CAD vendors, Autodesk®, Bentley® and Graphisoft®, provide implementations for both IFC and gbXML. There are on-going efforts, in a variety of domains, to extend IFC and gbXML schemas to represent more information (Huang, 2011).

Table 2-9 Comparison of schemas for interoperability

	IFC	gbXML	COBie
Format	EXPRESS	XML	Excel/IFCxml
Public (open source)			
Parametric Objects			×
Extensible			

The formats in Table 2-9 are all extensible; potentially, each can represent information for sustainability assessment (although gbXML was originally developed to capture information for energy analysis). However, currently, no single format suffices, as a complete data structure, to support sustainability assessment.

"[T]here is only a limited use of BIM to assist LEED certification compliance."
(Becerik-Gerber & Rice, 2010)

A building information model acts as a data container to hold project information, and to provide placeholders with a handle for data not yet available in the model. Currently, BIMs require additional data required for to meet the criteria in sustainable building design rating systems. Some of this data has to be defined (or otherwise augmented) in the BIM structure in coherent manner; other data come mainly from external sources. There are commercial BIM solutions, which tend to use proprietary data structures to represent building and other design information (graphical and

(18) BuildingSMART is an international organization with aims to improve the exchange of information between software applications used in the building industry, and actively supports open BIM.

non-graphical). Figure 2-5 illustrates the ideal data exchange situation between a source application, typically, CAD or BIM software, and a receiving application, typically, performance simulation or analysis such as energy audit, rainwater runoff, Computational Fluid Dynamics (CFD) and so on. Here, both the source and receiving application receive information in a platform neutral data structure, namely, Industry Foundation Classes (IFC). Again, the ideal data exchange involves only non-proprietary IFC files.

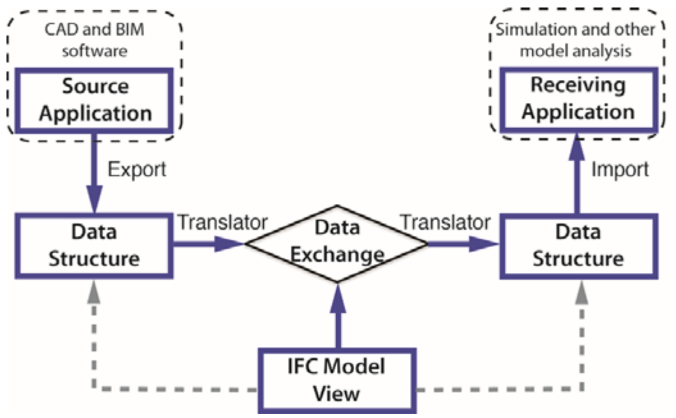


Figure 2-5 Ideal data exchange from software to another via IFC translation [Adapted from Eastman et al., 2008: Figure 3-3]

Industry Foundation Classes

"Despite certain reservations to IFC, i.e. that the standards is the lowest common denominator, having visible issue with 'round-tripping'[19], and imperfect certification process, IFC remains the only well-developed, non-proprietary and public data model for the AEC industry, existing today."
(Pniewski, 2011)

An IFC data model is an extensible framework to describe a large set of consistent building and construction industry data (Eastman, Teicholz, Sacks, & Liston, 2008). IFC specifies in EXPRESS (ISO (a), 2013), an entity relationship model comprising a (large) number of entities as an object-oriented hierarchy. In practice, IFC has multiple implementations—as such, even with good IFC import/export translators, exchanging useful data proves challenging. For this reason IFC translations from source applications have to be incrementally enhanced, and such enhancements

[19] 'Round-tripping' means importing IFC files into the application, which exported it in the first place, or importing it into any other application that supports IFC, without any loss of data or functionality.

need to be carefully considered for use by the exchanging applications. Recently, Autodesk® Revit® released an open source IFC exporter for Revit to provide greater flexibility with Revit IFC output (BIM Apps, 2011). There are specific viewers for IFC model geometry and properties, which display attributes of selected objects and provide means to view data in different sets of entities (Eastman, Teicholz, Sacks, & Liston, 2008).

> "[S]oftware vendors do not generally agree to exchange semantic data, and expose proprietary information and consequently disclose their trade secrets."
> (Pniewski, 2011)

IFC need not be the sole standard utilized in a BIM project, however, it may be employed in a partnership with other industry-standard product models or electronic data exchange formats that suit a particular domain. An IFC Object Model involves a large set of object definitions, but the individual specialty end-user applications implement only parts of it. To effectively support data exchange such applications need to be equipped with identical or overlapping parts or subsets of the IFC Product Data Model. Such subsets are called IFC Views, which comprise of individual IFC objects, and IFC Property sets (Psets). "The *IfcPropertySet* defines all dynamically extensible properties. The property set is a container class that holds properties within a property tree. These properties are interpreted according to their name attribute." (BuildingSMART, 2010) Psets belong to entities that have been defined in the IFC model and are comprised of properties, such as fire rating of a wall, cost of flooring material, etc.

> "[T]wo building modeling tools can have perfectly good translators to import and export data, but still be able to exchange very little useful data."
> (Eastman, Teicholz, Sacks, & Liston, 2008)

Figure 2-6 shows a pragmatic approach that is necessary for data exchange for particular IFC views. In such a workflow, definitions of IFC subsets would need to be specified and certified to maintain robustness of IFC. This diagram implies that there are always assumptions, factors and processes that are essential to developing tools for specific purposes, for example, sustainability assessment. Understanding the semantics and data structures that are imposed by industry standards is key to data exchange when navigating a given building model or dealing with availability of specific kinds of data. In (Krishnamurti, Toulkeridou, & Biswas, 2014) we describe a general process of data extraction from proprietary to non-proprietary BIM; and extraction of relevant chunks of data and/or data augmentation; in the process, we demonstrate that restructuring and re-representation of the building model is necessary in order to address domain specific queries. Such steps are integral for implementing tools that are flexible and adaptable for the differing and changing needs of the different stakeholders and professionals in the building industry in the context of exchange standards such as IFC.

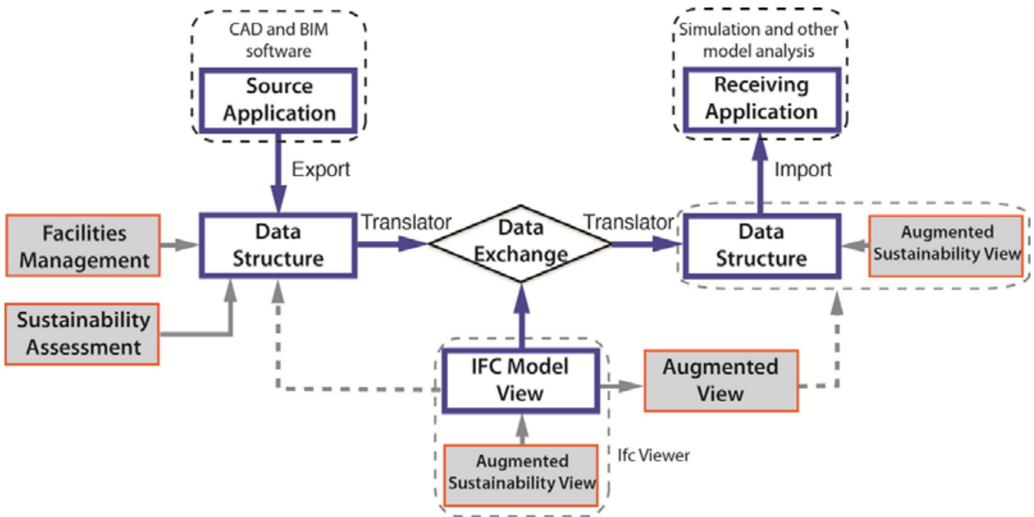


Figure 2-6 Pragmatic and extended data exchange from software to another via IFC translation

2.3.2 Construction Operation Building Information Exchange (COBie)

In order to share design information and sustainability related information from a software tool, a data structure is needed, which can integrate the necessary building information and sustainability evaluation requirements. To this end, the Construction Operations Building Information Exchange, (COBie) is explored as a suitable format for lightweight building model information exchange. COBie is primarily intended for the use of facility asset information delivery and managed assets (East B. , 2014). The nature and format of the COBie model provides designers and contractors access to electronic operations, maintenance, and asset management information as that information is created. In this data structure, information is cumulatively supplied during the design, construction, commissioning and handover phases of a building. Information includes lists of rooms and area measurements, material and product schedules, construction submittal requirements, construction submittals, equipment lists, warranty guarantors, and replacement part providers, which are normally included in several different places within current contracts. The objective behind the development of COBie is not to specify an alternative model for information that is required for building management, rather to provide a standard format for common information that can be derived from a building model. A criterion that underscores the development of COBie as an open exchange format is that it can accommodate facility handover data for both large custom and small public buildings with the least common denominator of technology allowing the widest possible set of project stakeholders.

A COBie model saves building owners and occupants from having to rekey information multiple times through out the life cycle of a project (East, 2012). The focus of COBie is on building information, not geometry; this format allows the focus to be on the relevant building information necessary for assessments. Figure 2-7 illustrates the organization of the data sheets in a typical COBie model, which is described in detail in Chapter 3, Section 3.4.2.

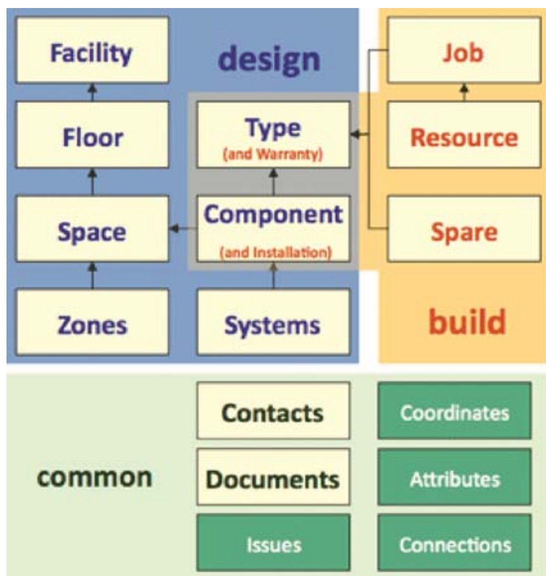


Figure 2-7 Summary of COBie data sheets (Adapted from (East, 2014)

A COBie file is not a complete building model. Instead, COBie is a subset of the building model, referred to as a "model view." The extent to which each COBie worksheet is filled depends on the project stage—it is role dependent: project team members enter data for which only they are responsible. For example, designers provide space and equipment locations; builders provide manufacturer information and installed product data (East B. , 2014). For large projects, COBie uses IFC-standard STEP and ifcXML formatted files. Smaller projects may exchange COBie data, displayed as spreadsheets, and directly update COBie data using these common spreadsheet programs (East B. , 2014). Figure 2-8 and Figure 2-9 show the 'Facility' sheet, cells are color coded for different types for information. Yellow indicates information that is required, orange indicates a foreign key, purple indicates external reference and green indicates information that is specified as required. The external reference includes the IFC object name such as IfcProject, IfcSite and IfcBuilding and unique identifiers as exported and translated from the building information model.

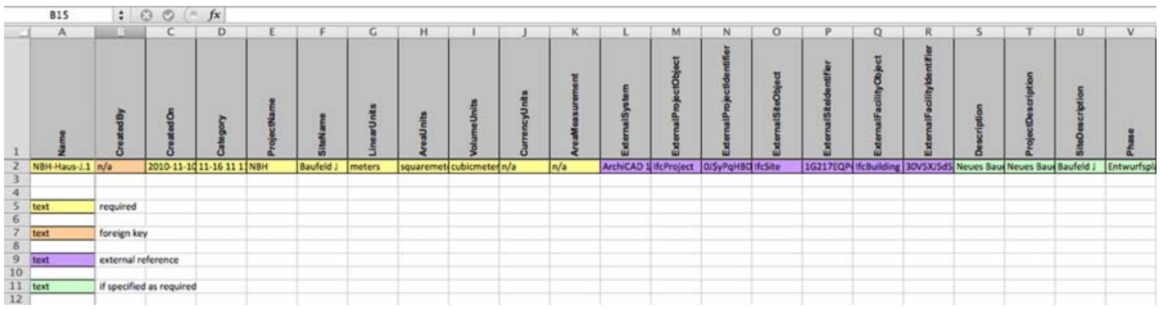


Figure 2-8 COBie Facility sheet with basic information

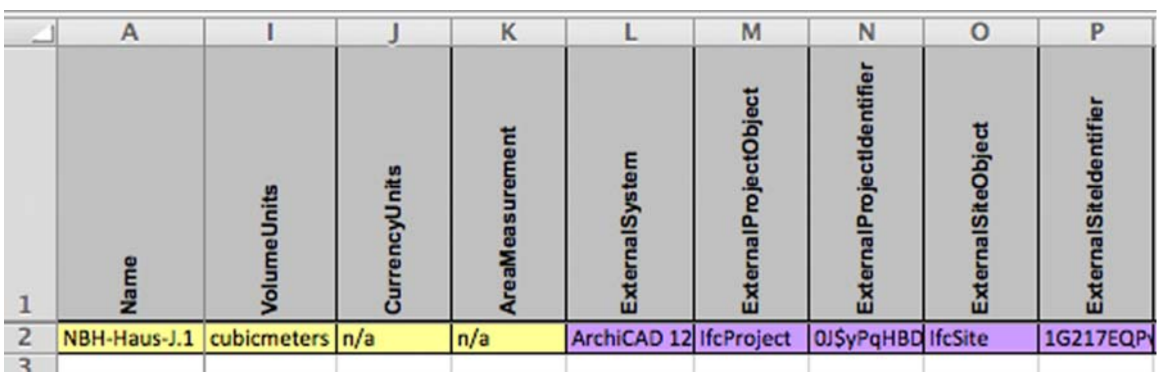


Figure 2-9 COBie Facility sheet with external references

2.4 Supporting Sustainable Information Organization

The discussions in Sections 2.1.1 (Sustainability Assessment Standards), and 2.3.1 (BIM and Information Exchange) present the nature of information, obstacles in information exchange and difficulties in integration of a passive tool within a design software. To organize and formalize the information so that it may be understood, shared and used by architectural, engineering, and construction management teams, an additional alternative option using ontology as a general framework has been explored for supporting sustainability information organization.

Ontologies, in general are created to facilitate the understanding about a specified domain by defining its entities, its classes, its function as and the relationships between all those (Montenegro, 2010). As tools and processes for designing and achieving qualities in buildings are constantly changing to meet the evolving requirements of rating systems (Williams D. , 2007), modeling an ontology provided a path to capture some of the domain knowledge required by rating systems and their relation with representative BIM elements for assessments in a digital environment.

The use of ontologies has moved from the realm of artificial intelligence to domain experts (Noy & McGuinness, 2001). One of the essential characteristics of ontologies is the sharing of information—shared knowledge enables the creation of common systems. In this regard techniques used to capture domain knowledge include vocabulary, taxonomy, and an ontological model for the user (Leite, 2009).

- A vocabulary is list of terms that have been enumerated explicitly, having unambiguous, defenition (Pidcock, 2003).
- A taxonomy is a "knowledge organization system." (Hlava, 2013) where vocabulary terms are organized in a hierarchical structure Figure 2-10; each term in a taxonomy is in one or more parent-child relationships to other terms (Pidcock, 2003). These knowledge organization systems are usually specific to a knowledge domain.
- Ontology is defined as an "explicit specification of a conceptualization." (Gruber, 1993) In general, "it is represented as a set of concepts within a domain and the description of realtionships between the concepts" (Akinci, Karimi, Pradhan, Wu, & Fichtl, 2008). That is, for this dissertation, a formal representation of a set of concepts within the building domain, using a shared vocabulary to denote the types, properties and interrelationships of those concepts with respect to sustainability assessment.

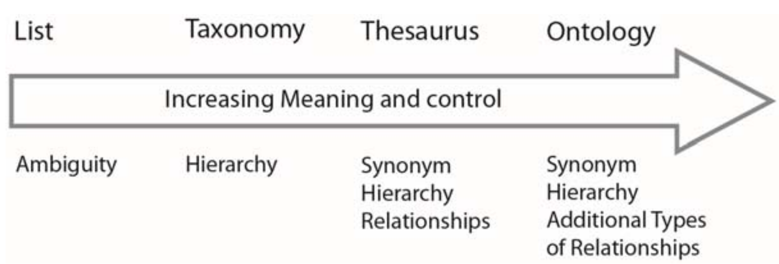


Figure 2-10 Structure of knowledge organization systems [Adapted from (Hlava, 2013)]

Many disciplines now develop standardized ontologies that can be used to share and annotate information in different fields. As a knowledge base, ontology can be developed akin to defining a set of data and their structure for other problem solving methods and software applications to use

(Noy & McGuinness, 2001). The role of formal ontologies in the architecture, engineering and contruction domain and sustainable building assessment domain are discussed next.

2.4.1 Approaches in the AEC Domain using Ontology

In the AEC domain there have been several examples in which ontologies are used to describe building related concepts (El-Diarby, Lima, & Fies, 2005) (Wang & Boukamp, 2011). Along with ontologies there have also been ontology-like or controlled vocabulary resources in the construction domain. For example, to demonstrate the power of bcXML the eConstruct project developed a taxonomy, bcBuildingDefinitions. LexiCon, initiated by researchers from The Netherlands, offers a vocabulary of terms for the construction industry (Lee, 2013) There are additional vocabulary resources in the building and construction industry such as BARbi, a reference data library in Norwegian, and the Standard Dictionary for construction vocabulary in French (Lima, Zarli, Storer, & Acevedo-Alvarez, 2007). In contrast to controlled vocabularies developed in Europe, in North America, a text-based classification, Omniclass, was developed within a single multifaceted approach (Lima, Zarli, Storer, & Acevedo-Alvarez, 2007).

Industry Foundation Classes are maintained by BuildingSMART [(20)] (buildingSMART (b), 2014). IFC is an AEC domain ontology which defines concepts, activities, objects and relationships among elements defined within the AEC/CAD domain. (Akinci, Karimi, Pradhan, Wu, & Fichtl, 2008) According to Corcho and Fenandez-Lopez (2002), an ontology should include the following minimal set of components: classes or concepts, and relations between concepts. In IFC concepts are known as entity sets. Concepts are classes that are organized in taxonomies that contain inheritance information. The International Framework for Dictionaries for BuildingSMART is an ontology framework in the building and construction related industries. It also contains mapping from IFC to ontologies within the library.

El Diarby Lima and Fies (2005) devised and developed taxonomy for the e-COGNOS project "as the first step in establishing a domain ontology for construction" (Leite, 2009). The taxonomy is based on six major domains to classify construction concepts: Process, Product, Project, Actor, Resource, and Technical Topics. Lee (2013) adopted the main concept structure of the e-COGNOS ontology and used it with new glossary and relationships to support embedded building commissioning processes. Despite these efforts, there is an ontological gap in the classification of

[(20)] BuildingSMART was formerly known as the International Alliance for Interoperability, which originally developed IFC sustainability for building domain applications, specifically, for assessing sustainability according to a rating system.

2.4.2 Approaches in Sustainable Design using Ontology

"[O]ntology will provide, in future research, a pattern encoding structure towards a computational model within the capabilities provided by the spatial data modeling of GIS" (Montenegro, 2010)

Montenegro proposes a pre-design ontology for (sustainable) urban program design. The system is organized according to a sequence of events, through stages, categories, methods, agents, and describes taxonomic levels and their inner relations.

Likewise, ontologies for sustainable design have been developed for various objectives (Yang & Song, 2009) (Succar, 2009). Yang and Song (2009) proposed an ontology for sustainable product design which model concepts of the sustainable design domain and show how it may be used across mutlidisciplinary teams. Rezgui and Marks (2011) present a sustainable construction ontology, which is used to develop a wide range of sustainability related services. Their ontology extends and enriches the latest specification of IFC with sustainable construction constructs that underpin industry energy calculations and compliance checking tools.

Recent research by Kasim and Rezgui has been to develop a BREEAM based ontology that covers the BREEAM domain of required information. To intelligently extract information from the developed enhanced IFC computational model that represents the knowledge. Ultimately, the aim is to implement an intelligent system enabling automated reasoning to conduct BREEAM assessment for buildings (Kasim, Rezgui, & Li, 2012).

Given the current development and interest in using ontologies as the basis of organizing and formalizing relationships of a domain, an ontology is developed from a rating system requriements perspective is presented in Chapter 5. The scope is limited to Water Efficiency as a category in sustainability measurement and depicts the relationships between necessary information that is formulated from analysis of rating system informational rquriements and available BIM elements, which is described in Chapter 3.

2.5 Summary

Design and construction require informational exchange between architectural, engineering, construction management teams throughout a project life cycle (Rezgui & Marks, 2011). Designers employ a combination of tools to aggregate information required for assessing sustainability targets. To reiterate, the amount of information (in paper-based and digital formats) is vast and complex. Moreover, the complexity increases with the added requirements that need to be shared and exchanged between various professionals when a building project is designed to meet sustainability standards such as LEED. To achieve the goal supporting sustainable design assessments in a more efficient way from the design stage, 1) rating systems were analyzed to identify information requirements, and 2) current support tools and information exchange standards were investigated.

In this dissertation, a framework is adopted to demonstrate integration of a passive tool such as LEED rating system with a building information model format to provide a more interactive way to support sustainability assessments. Using a well-organized lightweight BIM format such as COBie that is extended and used to map and manage necessary information for assessment creates the contention. The methodology presented in the following chapters is based on analyzing and aggregating the informational needs from a rating system and finding a suitable approach to integrate it with a building information model to provide assessment support.

Chapter 3

Requirements for assessment

This chapter describes the three steps taken to fulfill the first objective of this research, namely, to identify the informational needs for assessment. See Figure 3-1.

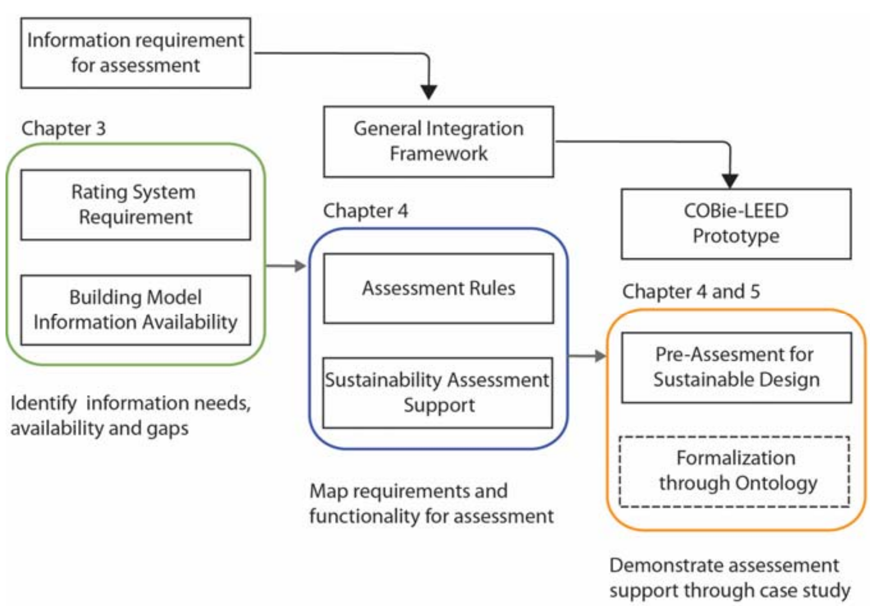


Figure 3-1 Research tasks and workflow

The steps are:

- Identifying the informational ingredients required by rating systems for sustainable building assessment
- Mapping requirements from rating system and information available form a building information model (For this work, Autodesk Revit® Architecture is used as the modeling software)
- Analyzing data requirements that need to be supplemented or augmented for integration with a building information model with a rating system

3.1 Information Requirement and structure

"[E]xisting practice-based method that had been developed to assist a dialogue between design team members and their clients–first setting priorities and targets for sustainability and then assisting later reviews and progress reports"
(Gething & Bordass, 2006)

Information for sustainable building assessment was elicited in the following ways: review of the literature, existing sustainable building rating system categories and credit requirements, and two case studies (Chapter 4, Section 4.1). A suitable structure for information requirement was arrived at, by taking a grounded theory approach (Glaser & Strauss, 1967). Information requirement for a database and development of a sustainability information framework (SIF) was created through analyzing an exhaustive list of data requirements from several rating systems (LEED 2.1, LEED 2009, BREEAM Office 2008, Green Star 2008, and CASBEE) mainly, for new construction, commercial building types focusing on requirements in the design phase. The process of requirement identification went through several iterations with Autodesk®. This allows for grouping by the concept of necessary measures, and formulates categories, subcategories and elements of sustainable rating systems within a general information structure that supports a framework. This framework is described in Chapter 4. In its own right, the framework can be used as a decision-making matrix.

3.1.1 Information Organization

Information required for rating based sustainability assessment is organized about the building life cycle, which is considered generically. The classification adopted in this dissertation is based on Geilingh (1988) who proposed a building life cycle according to the transition points shown in Figure 3-2. The periods between transitions are referred to as *phases*. The six phases of a building life cycle are: Feasibility, Design, Pre-Construction Planning, Construction, Operation and Management, and Decommissioning (Geilingh, 1998). Each phase is temporal, comprised components and activities occurring in that period of a building project. Associated with each phase is information required to fulfill sustainability rating evaluations.

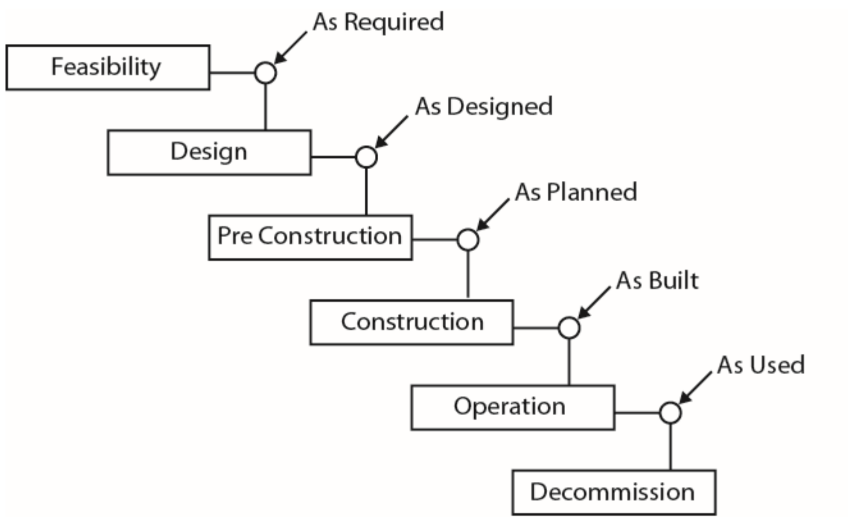


Figure 3-2 Classification of building life cycle (Geilingh, 1998)

Feasibility or Pre Design Phase

A feasibility study is usually undertaken prior to embarking upon any building project. Central to the study is a derivation of projects costs, expressed as a total amount or a combination of cash flow, other resources and possibly time from space quantities, mechanical systems, utilities and desired features. This is a vital phase as the decisions made here affect the overall environmental impact of the project. Teams, which are better informed, can contribute towards achievement of sustainable measures, choice of site and building forms and openings, material and systems selection—all important to the success of a project with ambitions to creating a sustainable design. Types of data for the different rating systems associated with this phase correspond mainly to project metadata from the building model.

Design Phase

"[A]spects architects need to consider, fairly early on is that of energy saving, cost and effect on the environment."
(Bennadji, 2004)

This phase covers inception of a project till execution of an actual building. Stages in the design phase include meetings, presentations, reviews and ultimately requiring approval from the client, design team and other stakeholders of the project. Activities include pre design, site analysis, schematic design, design development, construction documents, bidding and negotiations, and construction contract administration. According to Eastman (1999) this list of activities:

"Has been amalgamated from several sources including the IAI Code of Practice and the US Army Corps of Engineers submittal requirements."
(Eastman, 1999)

Each stage requires expertise and extensive data support for any kind of design undertaking, notwithstanding, when design aims to be sustainable.

The possibility of putting together the various kinds of technical, performance, economic aesthetic and other issues, fall to this phase. It involves various representations and analytic methods, often carried out by specialists on the design team. Although parts, namely, scale drawings, structural, electrical and piping components, and energy performances are integrated into a building model, in many cases, the computations are not straightforward—analyzing the performance of a building requires expertise and pre-preparation of many datasets. Again, to quote Eastman (1999):

"Only occasionally are they used iteratively to evaluate alternative designs and help select the ones with higher levels of performance."
(Eastman, 1999)

The key to sustainable design is energy efficiency; hence, requirements on the efficiency of systems are a priority. It is important to consider building envelope, material properties and internal loads as these too have synergies enabling reaching desired performance levels. In this phase, requisite sustainable design information comes from the project building model and external databases. Furthermore, preparations for simulations are essential.

Pre Construction Phase

This phase involves adding further relevant detail to the design documents, namely, detailed lists of associated materials and labor costs. From a sustainable design point of view, this guides a general contractor to carrying out tasks in a certain manner. For instance, product procurement from local sources has higher consideration in achieving overall targets of project sustainability. Decisions about safety, sourcing of labor, use of relevant codes and standards also contribute to the informational requirements.

Construction Phase

The construction phase starts with a construction schedule, which identifies units of construction and sequences of tasks. Construction requires a high degree of coordination among on-site crews and material deliveries from companies and fabricators. One of the main environmental impacts from construction arises from waste generation and energy use of equipment and machinery during on-site assembly. These are areas where sustainable design requires certain measures to be met. The quantities of waste material diverted from landfills through sorting, storing and recycling are measured in almost all rating systems. Emissions to soil, water and air from construction activities are taken into account in certain rating systems, for example, in BREEAM, section 12 - Pollution accounts for emissions to the air and water, such as credit Pol 06, aims at reducing heavy metal, and pollution from runoff to natural watercourses. In Green Globes the Emissions and Other Impacts category addresses air pollution in section F.1, contamination to waterways in section F.3 and Land and Water Pollution in section F.4. Closely related to construction is the commissioning of building systems, increasingly sought in order to ensure that buildings perform to the required level. Recording data relating to materials, resources, and machinery in this phase are pertinent.

Operation Management Phase

A building project is in reality a facility for its occupants who use the building. In the building operations phase, the significant impacts on resources relate to energy in form of heating cooling, and lighting. Other impacts result from potable water usage, and wastewater generation. Issues in facility management include component replacement and repair to ensure that systems operate as designed and efficiently.

__Decommissioning Phase__

"Building decommissioning and demolition generates primarily inert materials that have historically been land filled."

"The most common materials recycled are concrete and asphalt, wood, asphalt shingles, metals, and drywall."

(Ries, 1999)

Principal elements of demolition waste are wood and concrete, comprising two-thirds of the demolition waste of an average house.

3.1.2 Sustainable Building Information

Figure 3-3 shows the structure of the proposed sustainable building information structure. The subcategories comprise elements that are required for assessment by the rating system (in this case, LEED 2.1). The underlying assumption is that these 'credit elements' map to 'BIM elements' in the building information model. To reiterate, credit elements are required for the evaluation of a rating credit. BIM elements refer to entities ordinarily created by a BIM software, for instance, Autodesk Revit®—these correspond to elements such as walls, doors, and floors and so on, with attributes as area, volume, etc.

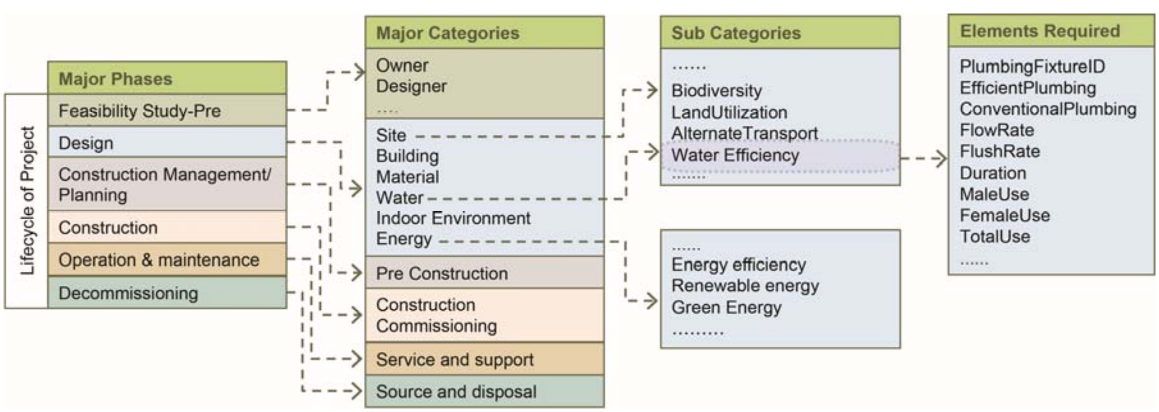


Figure 3-3 A structure for sustainable building information

Figure 3-4 illustrates how the requirements were identified for creating a building information database. Initially, building elements were identified based on the requirements for achieving credits in a rating system. As discussed in chapter 2, the list of credit elements was elicited from five major rating systems (BREEAM, LEED 2.1, Green Star, Green Globes and CASBEE) while working on the Autodesk project. These elements were then sought in the BIM and are called BIM elements.

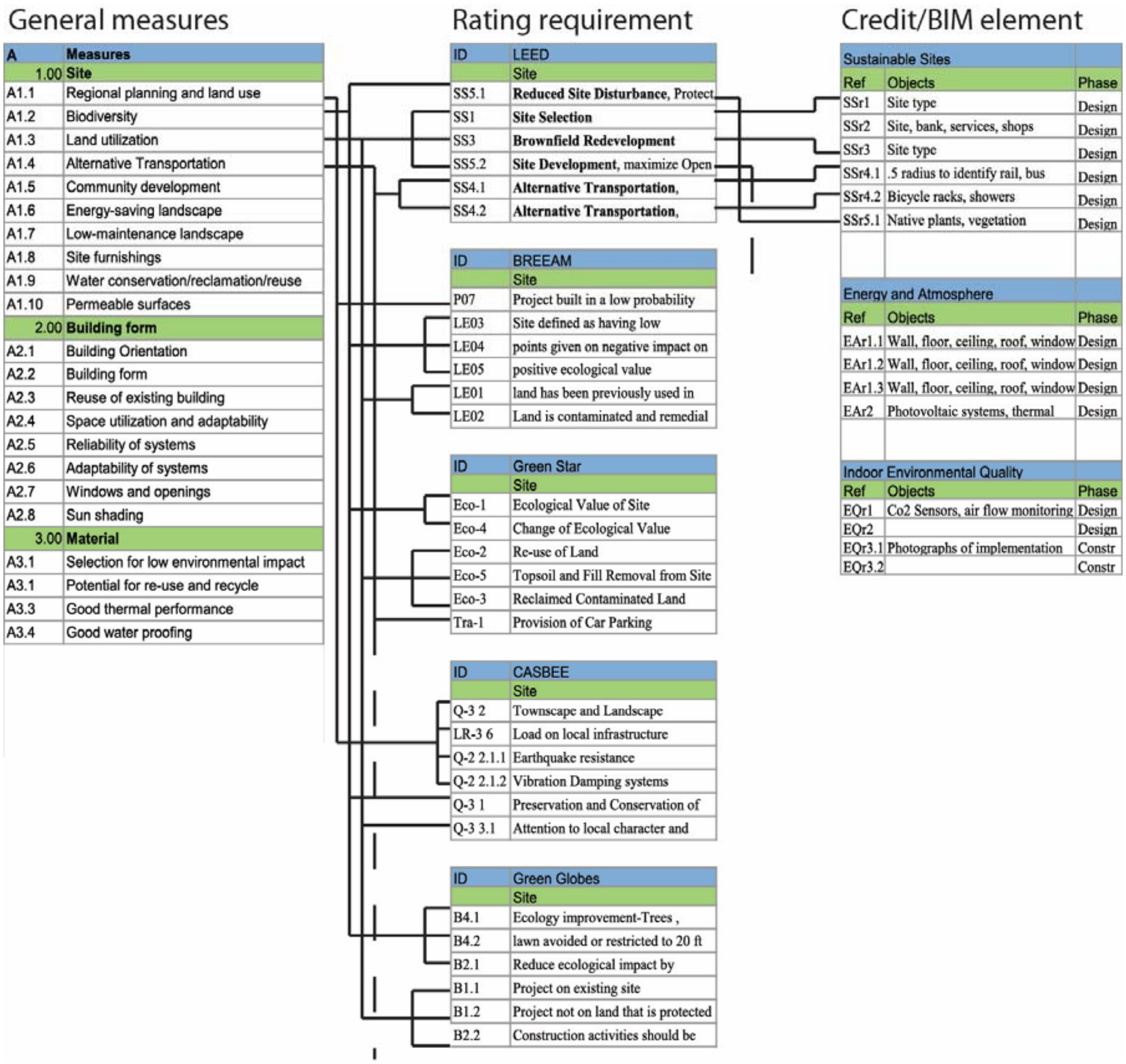


Figure 3-4 Relating rating information requirement to credit/BIM element

A 'Credit element' refers to an entity that is required for the evaluation of a certain sustainability credit, for scoring a point towards certification. Examples of Credit element include Efficient Water Fixture, Water Fixture Flow Rate, and Water Fixture Use Duration etc. A 'BIM element' refers to entities (objects and/or attributes) ordinarily contained in a typical building information model. Examples of BIM elements include walls, doors, and floors etc., which have attributes such as area, volume and so on. For this research, Autodesk Revit® was used as the principal BIM of inquiry. A general information structure was then created to hold these requirements.

Credit elements may correspond to real Revit elements/objects or their attributes. They may also correspond to quantities derivable by calculation from real Revit elements in which case, the Revit element is augmented with additional attributes to specify the BIM element. Credit elements may correspond to entities external to the Revit, but associated with real Revit elements, for example, flow rates of a plumbing fixture element, or the shading diameter of a plant element.

As the scope narrowed down and focused on different LEED versions over two selected credits, one example of LEED 2009 WEp1 Html template sample shows the kind of information required for Indoor Water Use Reduction in Figure 3-5. The PDF version (original from the website) is given in Chapter 4, Figure 4-11, Figure 4-12 and Figure 4-13. The information includes full time employee number, type of users, male and female numbers, type of water fixtures etc. In Chapter 4 the types of information is categorized and handled for filling the template from the COBie + model (Section 3.4.2).

WE Credit 3: Water Use Reduction

I, (Tenant, Project Manager, HVAC Engineer, Civil Engineer or Responsible party) John , declare that the project uses as least 20% less water than baseline fixture performance requirements of the Energy Policy Act of 1992

Flow Fixture Type	Water Use [gpm]	Duration[sec]
Conventional Lavatory	2.5	15
Low-Flow Lavatory	1.8	15
Kitchen Sink	2.5	15
Low-Flow Kitchen Sink	1.8	15
Shower	2.5	300
Low-Flow Shower	1.8	300
Janitor Sink	2.5	15

Flush Fixture Type	Water Use [gpf]
Conventional Water Closet	1.6
Low Flow Water Closet	1.1
Ultra Low-Flow Water Closet	0.8
Composting Toilet	0.0
Conventional Urinal	1.0
Waterless Urinal	0.0

Design Case Table

Flush Fixture Type	Daily Uses	Flow Rate [gpf]	Duration [flush]	Occupant users	Sewage Generation [gal]
Water Closet(Male)	0	1.1	1	150	0
Water Closet(Female)	0	1.1	1	150	495
Composting Toilet(Male)	0	0.0	1	150	0
Composting Toilet(Female)	0	0.0	1	150	0
Waterless Urinal(Male)	1	0.0	1	150	0
Waterless Urinal (Female)	0	0.0	1	150	0

Figure 3-5 Credit elements required to fill LEED 2.1 WE3 Html template sample

Once the credit elements were identified they were mapped to BIM elements available from the Revit model is shown for LEED WE3 assessment (Figure 3-6). As shown there are some elements that are not directly available from the model such as MaleUses (number of uses by male occupants in the building) – such information has to be either defined in the Revit model or stored separately.

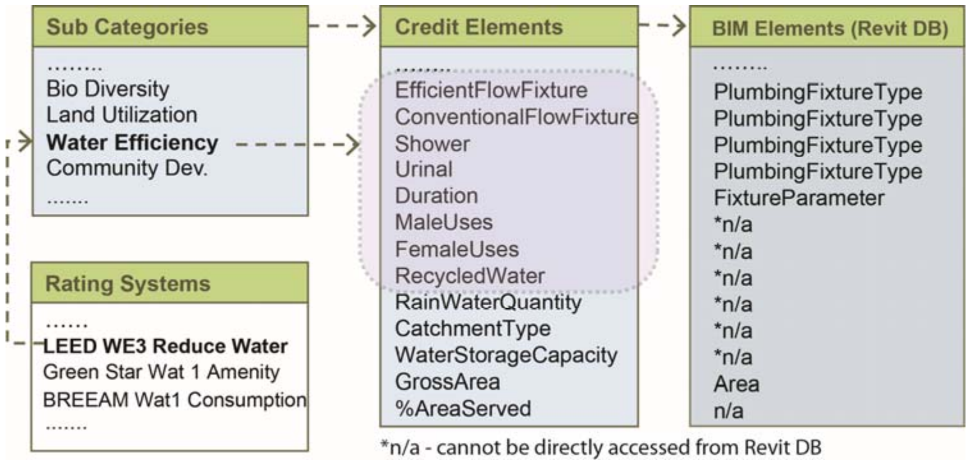


Figure 3-6 Credit element and BIM element for LEED 2.1 WE3

Revit objects known as elements are also considered before the Revit BIM model is exported into the IFC format to be augmented to specify the BIM element. A credit element may also correspond to an entirely new BIM element or quantity that is not associated with any Revit entity, for example, occupants with attributes such as male occupant number, part time or full time occupants, ground cover with all its attributes such ground cover type e.g., grass, shrub, paved etc.

3.2 Mapping Rating Requirements to Building Information Modeling Software

Primary developing and testing of the information structure in Figure 3-4 was carried out through an analysis of the information available in Revit Architecture. Tests were carried out, initially, in Revit Architecture 2009, and subsequently, in Revit Architecture 2010. Requirements were identified iteratively based on feedback from the Autodesk® research team members (Krishnamurti, Biswas, & Wang, 2010). Rating requirements were mapped to BIM elements from the perspective of the following five rating systems—LEED 2.1, Green Star, BREEAM, CASBEE and Green Globes.

In this research BIM objects also referred to as 'Revit elements' are classified as i) basic Revit elements; ii) extensible Revit elements; and iii) external objects and databases. For example in Revit Architecture, Revit elements such as wall, floor, column, door, window, and plumbing fixture belong to classes known as 'Revit Family' in the Revit API (Application Processing Interface) shown in Figure 3-7. Families can group objects that have a common set of parameters (properties) and identical use.

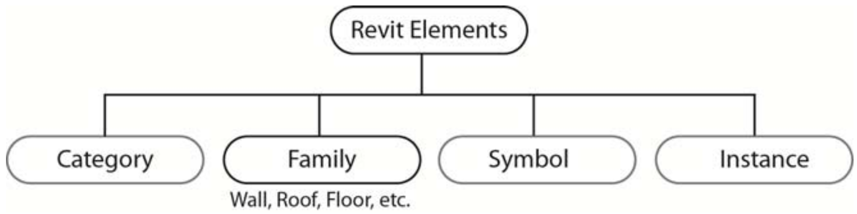


Figure 3-7 Revit element classification

Each of the objects in a Revit family has some basic standard properties. In Figure 3-8 a plumbing fixture family shows Materials and Finishes, Plumbing, and Mechanical parameters, these are standard parameters of this Revit family.

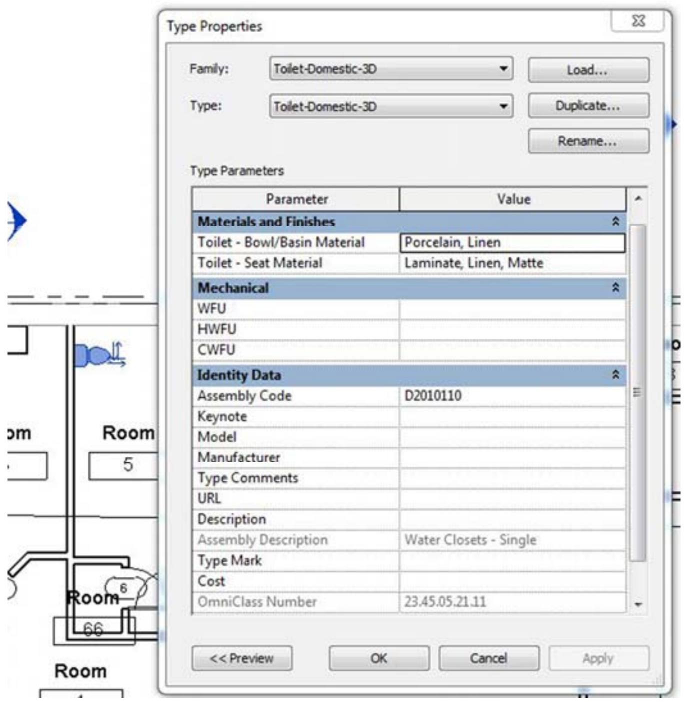


Figure 3-8 Revit plumbing family type with standard parameters

In order to evaluate for LEED credit Water Efficiency (WE3—Water use reduction), ‘FlowRate’ and NumberOfUses’ are necessary, in addition to the number and different types of plumbing fixtures. It is possible to edit the family and create a new family with additional ‘shared parameters’ that fulfill the requirements. This is shown in Figure 3-9, the ‘Other’ category has two new parameters. Creating a shared parameter for the family ensures that the customized parameter is exported to the IFC format.

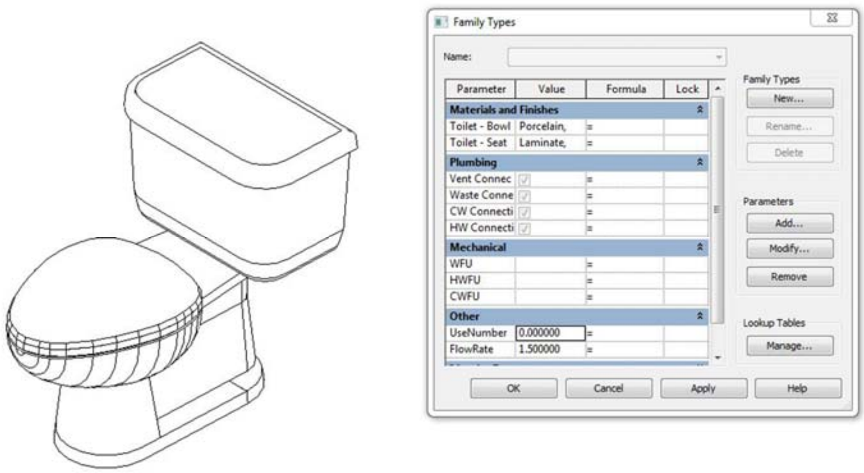


Figure 3-9 Revit plumbing family type with added parameters

As discussed in Section 2.3.1, translators of different software have limitations, and one has to be aware of the mapping categories when exporting, otherwise information is lost or put in generic categories (AUGI, 2012). The study shown below demonstrates that within the same software when a model is exported from its proprietary format to non-proprietary format such as IFC there are problems. The first warning appears when opening an IFC file created in Revit Architecture. To resolve the error elements were deleted saved as a Revit file and then exported to IFC again. Figure 3-10 and Figure 3-11 shows the warning when opening the file. After three iterations of this process and deleting the elements that caused the warnings the model could be opened without errors. Comparing the starting and ending state of the model in Solibri model viewer reveals that 5 objects were removed and 270 objects were modified (Figure 3-12).

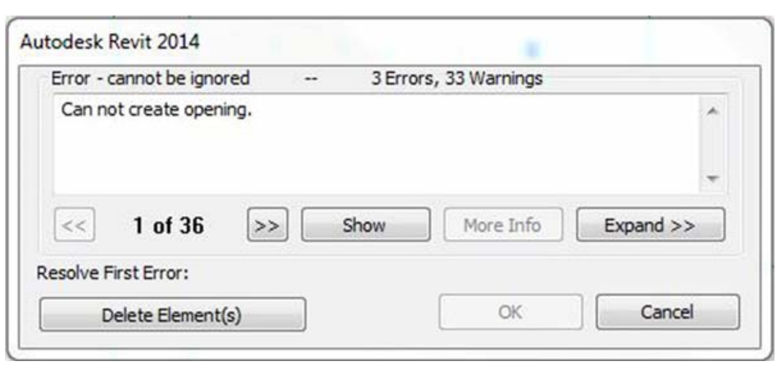


Figure 3-10 Warning message when opening IFC file created in Revit first time

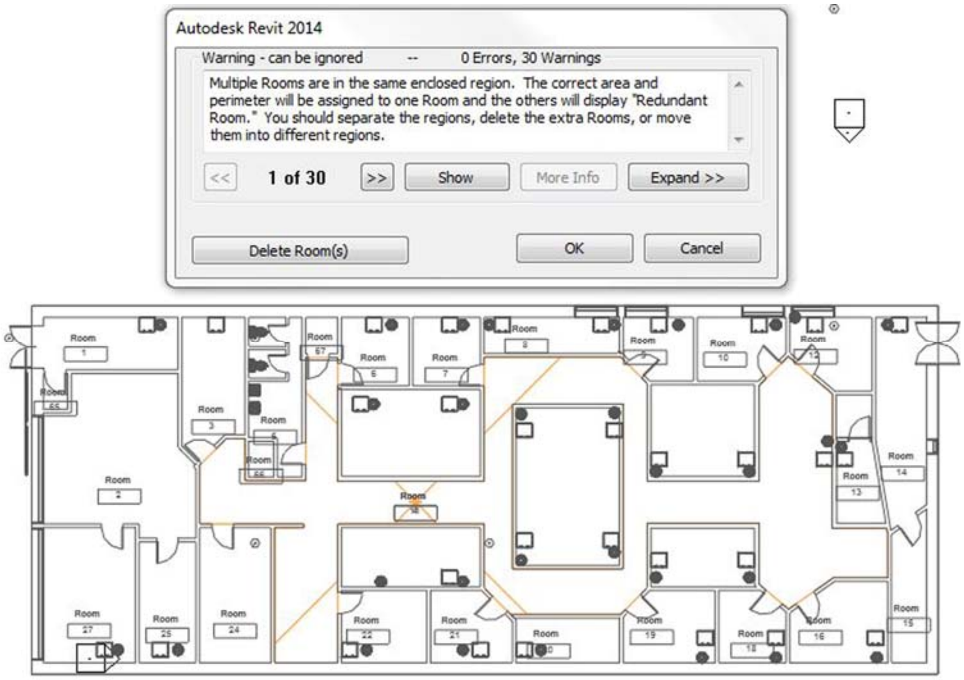


Figure 3-11 Warning message when opening IFC file created in Revit second iteration

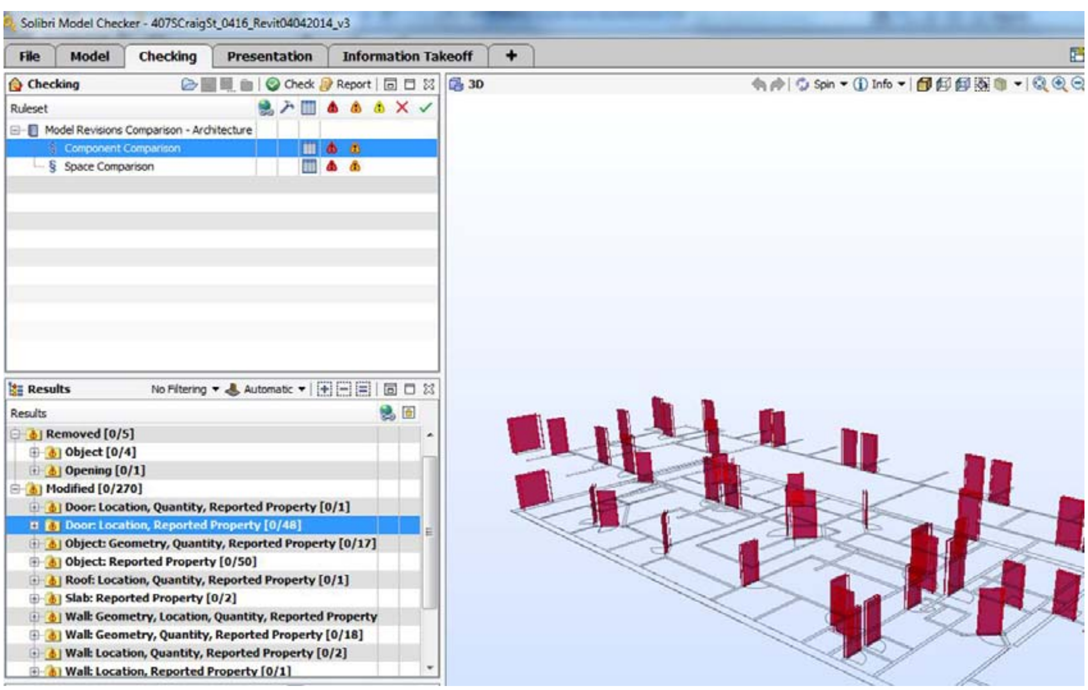


Figure 3-12 Model comparison using Solibri model checker

Exporting to a database format can also store information under generic categories. In Figure 3-13 the Revit model with added parameters was exported to a database format and it shows the unique ID and name 'Toilet-Domestic' of the element, however, it does not show the corresponding IFC object. In order to work with a non-proprietary data format, this model can be viewed in IFC viewer software such as Solibri Model Viewer (Figure 3-12).

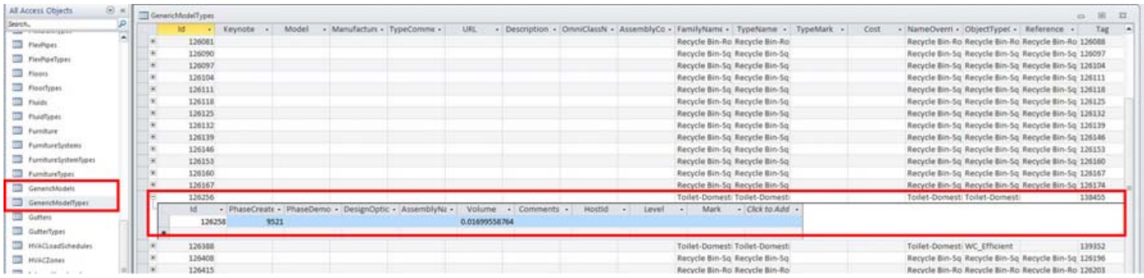


Figure 3-13 Revit plumbing family type exported in database form

Experience from the Autodesk project lead to the conclusion that Revit elements could be customized with parameters for catering to LEED 2.1 requirements, however a significant amount of data still needed to be supplemented. The summary can be seen in Section 3.4.1. Given the current state of information exchange from a building information model to a non-proprietary form, it is assumed that there will be information loss, due to inherent data structures of software and translators. IFC is not without its problems and limitations. However,

"IFC is the 'lowest common denominator', which results with the most of the functionality found in proprietary applications being substantially reduced to the level of functionality carried by other interfacing applications."
(Pniewski, 2011)

Keeping the limitations of data exchange in mind it was concluded that the format of exported information should show the corresponding IFC entity. Having the core IFC entities of a model at a minimum would provide as a starting point for identifying information present and necessary for sustainable assessments. Section 3.4.1 summarizes informational needs in Revit 2009 and 2010 as found in the Autodesk study; as this did not include references to IFC entities, it became apparent that it would be difficult to extend the work for non-proprietary uses. Section 3.4.2 summarizes informational needs from a COBie file format that was converted from the Revit file. The COBie file contains the originating IFC entity, thus this offered a platform to use, and suggest possible extensions suited for sustainability assessments.

3.2.1 Identifying Information Requirements For Software

In order to identify and map requirements, we first create a list of categories, subcategories, and credit elements based on the building phases in design. The phases and structure of information organized has been discussed in Section 3.1.1. Second, credit elements are prioritized based on the number of times they were used for assessment, primarily for LEED 2.1. Third, these credit elements are organized in a database, which is mapped to, primarily, Revit BIM elements and 'corresponding' IFC entities (Section 3.3). Fourth, gaps in the building information model are analyzed and a list of credit elements is suggested for augmenting the model to make it suitable for assessment querying (Section 3.4).

There are similar approaches in the literature to creating frameworks for different aspects of sustainable design (Weerasinghe, 2007); (Keysar, 2007); (Olbina & Beliveau, 2007). Each of the credit elements listed is given a short description, and is placed under a suitable category and sub categories created. The credit elements are mapped to requirements of different credits in the rating system, and to BIM elements along with their IFC entities Table 3-2, Table 3-3, Table 3-4.

As a measure of the priority of a credit element, its number of occurrences within the sustainable building information structure is counted against each rating system criteria. The difference in the priority of the elements is seen through this count. The number of times an element of LEED 2.1 occurs is shown in the graph in Figure 3-14 for each credit in the sustainability information database (Section 3.3).

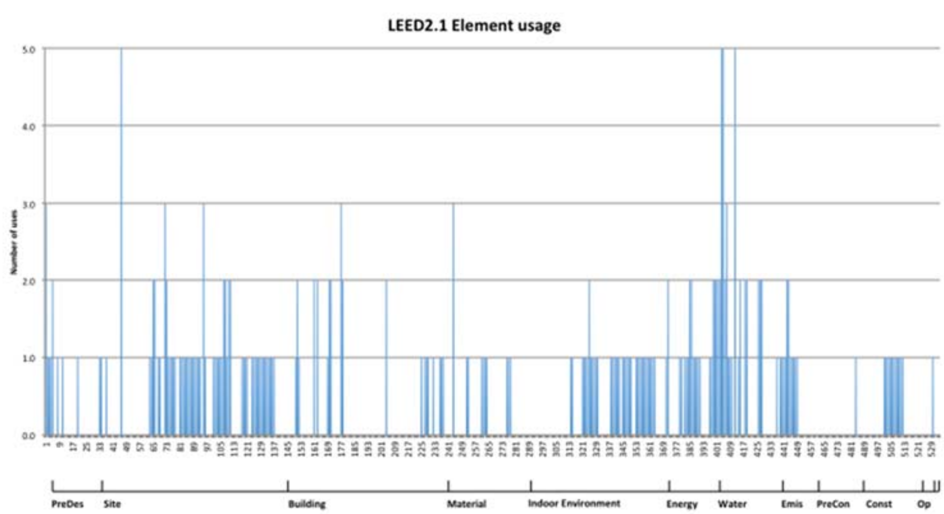


Figure 3-14 Occurrences of credit elements in framework for LEED 2.1

The X axis lists the credit elements in the framework and follows the main design phases as discussed in Section 3.1.1. Credit elements for Pre Design , Design (comprising of Site, Building, Material, Indoor Environment, Energy, Water, and Emissions), Pre Construction, Construction, Operation and Decommissioning are shown left to right on the X axis. the Y axis denotes the number of times a certain credit element has been used in the evaluation of a design credit for the chosen rating system. Multiple uses of the credit same element show that it is required by more than one credit. Credit elements can be used for credits in different categories For instant, credit elements such as 'CapturedRainWaterQuantity' in the water category is mainly used in order to calculate water efficiency credits; however, it is also used in the sustainable sites category where water effieicency for irrigation is a consideration.

Table 3-1 lists some of the more frequently used elements in evaluating a design with respect to LEED NC 2.1 and their occurrence count. Similar element occurrence tally are given in Appendix A for Green Star, BREEAM, CASBEE and Green Globes rating systems.

Table 3-1 Number of times an element is required in LEED 2.1

Sub Category ID	Ref Number	Credit Element Name	LEED 2.1 Uses
B_1_2_14	47	AreaVegetatedRoof	5
B_6_1_6	404	UseCapturedRainWater	5
B_6_1_7	405	UseRecycledWasteWater	5
B_6_2_5	412	CapturedRainwaterQuantity	5
B_1_4_22	96	FullTimeOccupant (FTE)	3
B_2_6_1	178	HVACSystemCompliance	3
B_3_1_9	245	MaterialManufacturer	3
B_6_1_9	407	VegetationType	3

By counting the occurrences of elements required by the different rating systems, it is possible to prioritize their usage for assessments and consider how they relate to BIM elements in the first phase. See Figure 3-15. By the data, the elements referred to the most number of times query if the HVAC system complies with standards as stipulated by ASHRAE. Initially before representing the HVAC system component compliance requirements separately such as heating, cooling and ventilation systems, it resulted in an outlier spike in the graph Figure 3-16. In Figure 3-16 the

HVAC system components are expanded to accommodate more specific credit elements related to the various components and thus the distribution changes.

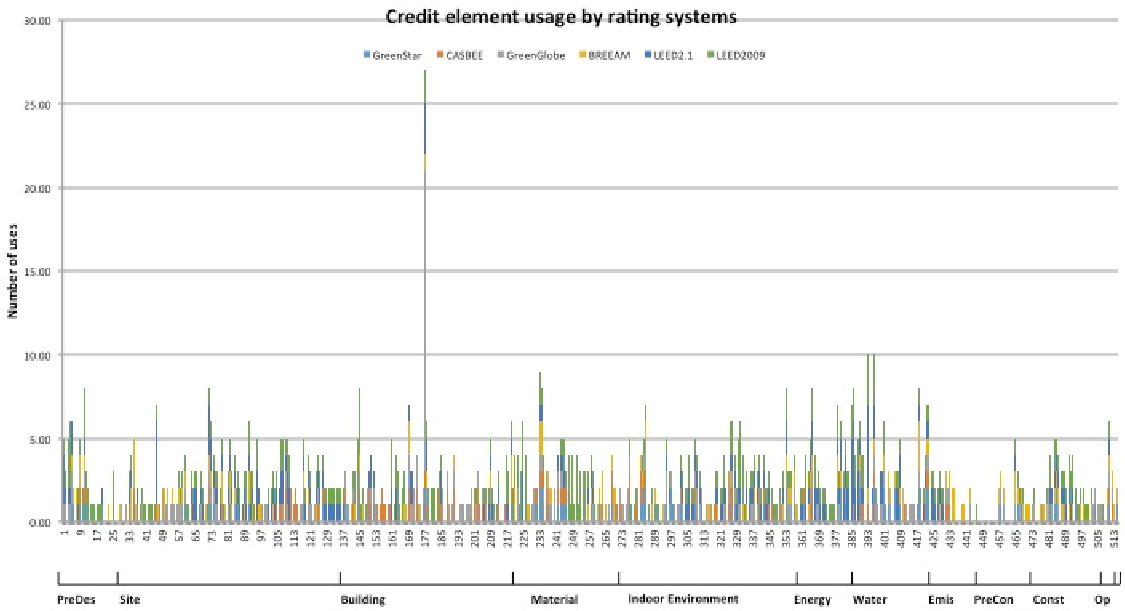


Figure 3-15 Occurrences of credit elements from all rating systems HVAC combined

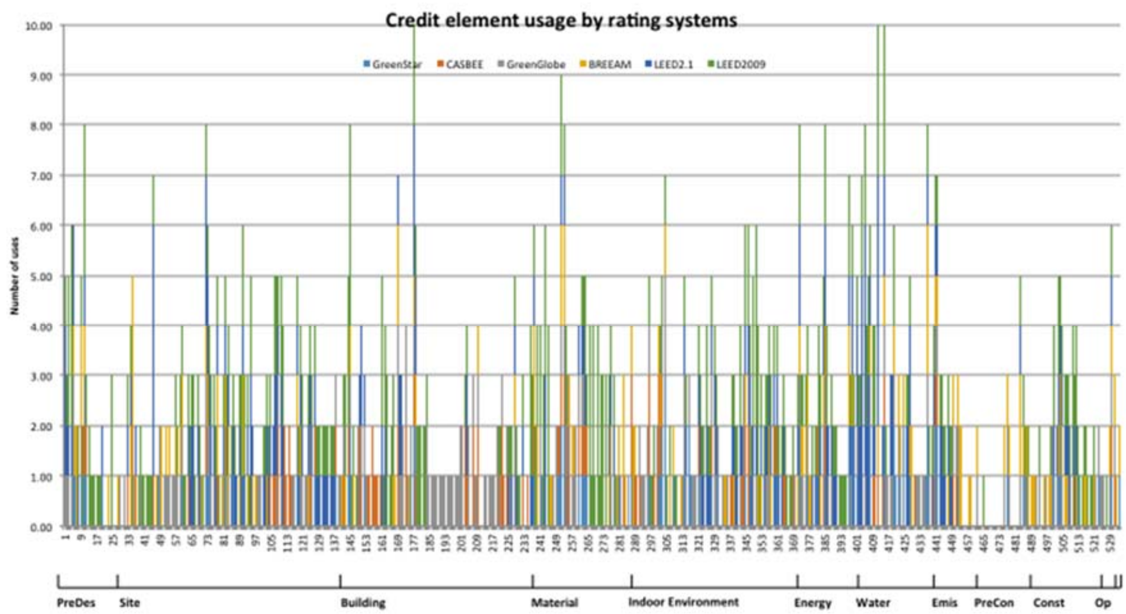


Figure 3-16 Occurrences of credit elements from all rating systems HVAC expanded

The group of credit elements that are used with a frequency between 8 and 10 times are listed in Table 3-2. These credit elements include:, captured rainwater quantity, recycled waste water quantity, reuse of material, material with recycled content, buildings total energy requirement, reduction of energy use from baseline, occupant number, site area, building gross area, and energy simulation.. In addition to energy being the most heavily weighted both in terms of points it also requires some of the highly used credit elements from the model. Thus the prerequisite for minimum energy performance was selected for demonstration in the Energy Efficiency category. The second credit chosen, which is in the water efficiency category: Indoor water use reduction also had credit elements being queried in the high frequency group.

Table 3-2 Credit elements prioritized according rating system use (8-10 times)

Credit Element Name	Process	Standard*	Custom*	IFC Entity
HVACSystemCompliance		None	NA	No
CapturedRainwaterQuantity		None		IfcNumericMeasure
RecycledWasteWaterQuantity		None		IfcNumericMeasure
MaterialReuse	NA	Beam, Floor, Door, etc.	Yes	IfcBeam, IfcSlab, IfcDoor, IfcMaterialProperties
PreAndPostConsumerContent	NA	Beam, Floor, Wall, Door, etc	Yes	IfcBeam, IfcSlab, IfcWall, IfcDoor, IfcMaterialProperties
TotalEnergyRequirement	Process	None	NA	IfcNumericMeasure
ReduceEnergyFromBase	Process	None	NA	No
OccupantNumber	NA	None	NA	IfcNumericMeasure
SiteArea	NA	Site	Yes	IfcSite, IfcQuantityArea
BuildingGrossArea	NA	Area	Yes	IfcBuilding, IfcQuantityArea
EnergySimulationType	NA	None	NA	IfcDocument

* Standard and custom respectively refer to elements are standard in Revit or to be customized

The next group comprises of credit elements occurring between 6 to 7 times, these are shown in Appendix B. The least used credit elements are those only for a specific rating system. All other elements are used between one to five times. Elaboration of credit elements in the subcategories of the design phase has been the focus in this research. Table 3-3 shows the credit elements needed to evaluate ‘Indoor Water Use Reduction’ for LEED 2.1, BREEAM and Green Star.

Table 3-3 Credit elements mapped to rating systems for water use reduction

Credit Element Name	BIM Element	IFC Entity	LEED 2.1	BREEAM	Green Star
EfficientFlowFixture	Plumbing FixtureType	IfcSanitary TerminalType	WE3	Wat1	Wat 1
ConventionalFixture	Plumbing FixtureType	IfcSanitary TerminalType	WE3	Wat1	Wat1
Urinal	Plumbing FixtureType	IfcSanitary TerminalType	WE3	Wat1	Wat1
Showers	Plumbing FixtureType	IfcSanitary TerminalType	WE3	Wat1	Wat1
FixtureFlowRate	Fixture Parameter	Parameter of IfcSanitary TerminalType	WE3	Wat1	Wat1
UseDuration	Fixture Parameter	Parameter of IfcSanitary TerminalType	WE3	Wat1	Wat1
MaleUseNumber	NA	IfcQuantity Count	WE3		
FemaleUseNumber	NA	IfcQuantity Count	WE3		
FullTimeOccupant(FTE)	NA	IfcQuantity Count	WE3		
ResidentNumber	NA	IfcQuantity Count	WE3		
TransitentNumber	NA	IfcQuantity Count	WE3		
WaterStorageCapacity	NA	IfcNumericMea sure		Wat 1	
RecyledWaterQuantity	NA	IfcNumericMea sure	WE3	Wat 1	Wat 1
GrossArea	Floor Area	IfcQuantityArea			Wat 1
RainWaterQuantity	NA	IfcNumericMea sure	WE3	Wat 1	Wat 1
CatchmentAreaType	Area	Parameter of IfcArea		Wat 1	

In the same manner Table 3-4 shows some of the elements needed to evaluate the 'Alternate Transport' requirement for the three given rating systems: LEED 2.1, BREEAM and Green Star. The Revit family represents the BIM element and the IFC entity is shown in the IFC column. It may be noted that these IFC entities in most cases would require specification of extended 'Property

Sets'. IFC Property sets are intended to standardize a basic set of properties, whereas other property sets can be regionally defined or agreed upon in projects (Halfawy & Froese, 2005).

Table 3-4 Credit elements mapped to rating systems for alternate transportation

Credit Element Name	BIM Element	IFC Entity	LEED 2.1	BREEAM	Green Star
BicycleRacks	Bicycle stand	IfcObject	SS4.2	Tra 03	Tra-3
Showers	Plumbing Fixture	IfcSanitary TerminalType	SS4.2	Tra 03	Tra-3
DistanceToShower	Line	IfcQuantityLength	SS4.2	Tra 03	
AdequteLighting	Lighting	IfcLightFixtureType		Tra 03	
StandDistanceToEntrance	Line	IfcQuantityLength	SS4.2	Tra 03	
FTE	NA	NA	SS4.2		Tra-3
Area	Floor Area	IfcQuantityArea			Tra-3

As measures are further decomposed into credit elements and attributes, relative methods for evaluating credits from each rating systems are organized in a database format. Through this mapping credit elements that are presently standard in the building information model can be identified; this, in turn, determines what is needed for an overall evaluation of a building design from a sustainability perspective. Evaluation of a credit requirement has three main components; the relevant elements and their parameters, relevant methods, and external references needed for assessment.

3.3 Sustainability Information Database

The sustainable building information structure covers the requirements from the viewpoint of a sustainable building design rating. The database structure for the associated measures of the rating system is organized as a hierarchy of elements and parameters. These map back to the six phases of building life cycle (A to F) that are described in Section 3.1.1. The main phases are organized by category. In the 'design' phase, in particular, they have been organized under seven category headings, namely, site, building, material, indoor environment, energy, water and emissions. Table 3-5 shows the phases and categories.

Table 3-5 Phases and categories in the database

Phases	**Categories**
A Feasibility Study-pre design	A_1 Decision Making
B Design	B_1 Site B_2 Building B_3 Material B_4 Indoor Environment B_5 Energy B_6 Water B_7 Emissions
C Construction Management/ Planning	C_1 Pre construction
D Construction	D_1 Construction D_2 Commissioning and Handover
E Operation and maintenance	E_1 Service and Support
F Decommissioning	F_1 Source and Disposal

More detail is given in the sub-categories. A partial list of the credit elements in category B_6 Water is shown. The water category is sub divided into sub categories B_6_1 Water Irrigation Reduction (Table 3-6); B_6_2 Water Reuse and Treatment; and B_6_3 Water Fixture and Equipment Use (Table 3-7).

Table 3-8 illustrates the relationship between sub categories and their credit elements. Columns respectively represent the credit element ID; description; return value type—namely, Boolean, number, string, etc.; a type indicating whether it is simple (single value) or complex (multi-valued); Revit elements, if any, associated with the credit element; and lastly, whether the Revit element needs extension (that is, customization), or if external data is required. Some of the extensions are given in tables identified by the credit element name. This database was used as a basis for structuring, identifying and using the data with the Autodesk® funded Sustainable Building Information (SBIM) project.

Table 3-6 Credit elements in subcategory B_6_1 Water Irrigation Reduction

Credit Element ID	Credit Element Name
B_6_01_01	PotableWaterQuantity
B_6_01_02	SpeciesFactor
B_6_01_03	IrrigationType
B_6_01_04	DensityFactor
B_6_01_05	MicroclimateFactor
B_6_01_06	CapturedRainWater
B_6_01_07	RecycledWasteWater

Table 3-7 Credit elements in subcategory B_6_3 Water Fixture and Equipment Use

Credit Element ID	Credit Element Name
B_6_03_01	EfficientFixtureFlowRate
B_6_03_02	WaterUseRegualtions
B_6_03_03	ProcessWaterQuantity
B_6_03_04	WaterControlMetering
B_6_03_05	PlumbingAndDrainage
B_6_03_06	WaterlessFixture
B_6_03_07	ConventionalFixtureFlow
B_6_03_08	FireSystemWater
B_6_03_09	FixtureUseNumber
B_6_03_10	FixureUseDuration

Table 3-8 Credit elements in sub category B_6_1 and B_6_3

Credit Element ID	Credit Element (CE) Description	CE Value	CE Type	Revit Element	Parameter	IFC Entity
B_6_01_01	Amount of water used annually	Number	Simple	Plumbing Fixture	Extension	IfcQuantityVolume
B_6_01_02	Coefficient used to measure the amount of water used by different species	Number	Complex	n/a	External	n/a

Credit Element ID	Credit Element (CE) Description	CE Value	CE Type	Revit Element	Parameter	IFC Entity
B_6_01_03	Type of irrigation and coefficient used	Number	Complex	n/a	External	n/a
B_6_01_04	Coefficient used to determine plant density	Number	Complex	Plant	Extension	n/a
B_6_01_05	Coefficient used to measure climate factor	Number	Complex	n/a	External	n/a
B_6_01_06	Amount of rainwater used	Number	Complex	n/a	External	IfcQuantityVolu me
B_6_01_07	Amount of recycled water used	Number	Complex	Plumbing Fixture	Extension	IfcQuantityVolu me

……

B_6_03_01	Fixture flow rates for efficient fixtures	Number	Complex	Plumbing Fixture	Extension	IfcSanitary TerminalType
B_6_03_02	Water use guidelines per reference	String	Complex	n/a	External	IfcProcess
B_6_03_03	Water used by dishwasher, cooling towers	Number	Complex	n/a	External	IfcWaterProperty
B_6_03_04	Metering, sub metering for use and leak detection	Boolean	Complex	Plumbing Fixture	Extension	IfcControl
B_6_03_05	Plumbing and drain-age systems and features	String	Complex	n/a	External	n/a
B_6_03_06	If the fixture is waterless	Boolean	Complex	Plumbing Fixture	Extension	IfcSanitary TerminalType
B_6_03_07	Fixture flow rates for conventional fixtures	Number	Complex	Plumbing Fixture	Extension	IfcSanitary TerminalType
B_6_03_08	Water used can be reused and shut off valves on each floor	Boolean	Simple	n/a	External	IfcValveType
B_6_03_09	Number of times a fixture is used by male, female	Number	Complex	n/a	External	IfcQuantityCoun t
B_6_03_10	Duration the fixture is in operation	Number	Simple	n/a	External	IfcQuantityCoun t

……

3.4 Information Augmentation for Assessment

Proprietary software applications, provided by such vendors as Autodesk®, Bentley®, Graphisoft®, Nemetschek Vectorworks®, specify their own internal building information models. In order to have these models accessible to applications outside of the proprietary environment, data needs to be extracted in a non-proprietary format. Inevitably, there is information loss; on the positive side, the tradeoff is platform independence. There are public widely recognized data exchange standards data exchange formats, which were discussed in Chapter 2: IFC; ISO standards; IFCXML and gbXML; BIM templates; and COBie. In the sequel is discussed the relationship between Revit, a proprietary building information modeler, and COBie, an open source format.

3.4.1 Information Augmentation for BIM software

Gaps in Revit were investigated to determine which BIM objects and which Revit objects were relevant for sustainability assessment, and of the latter, which required extension. Since Revit maintains a relational database, it is possible, by default, to make these extensions as a required part of the element property list. A toggle is set whereby the extended parameters are only made available when one wants to explore sustainability of a design project. Otherwise, doing so overloads the Revit model, as it would contain element properties not be needed for other kinds of design projects.

LEED was chosen as the first primary sustainable building rating system requirements to be investigated from a Revit BIM element/family perspective. Table 3-9 shows the minimum number of extensions required to Revit BIM element to meet the requirements of LEED NC 2.1. Among these, the Material and Resources category of LEED uses the most number of existing Revit BIM element. These require the most number of extensions as well.

Table 3-9 Revit BIM elements by family type in LEED evaluation

LEED Category	Revit BIM elements by Family Type	Minimum Number of Extensions to Object
Sustainable Site	Lighting Fixture	2
	Planting	4
	Specialty Equipment	—
	Entourage	4
	Mass	—
	Site	9

LEED Category	**Revit BIM elements by Family Type**	**Minimum Number of Extensions to Object**
Water Efficiency	Plumbing Fixture	3
Energy and Atmosphere	Mechanical Equipment Lighting Fixture	6+ 3
Material and Resources	Ceiling Column Curtain Panels/System Door Floor Furniture Roof Structural Column Stair Structural Frame Structural Foundation Structural Beam System Structural Column Wall Window	6 6 4 6 6 6 6+ 6 6 6 6 6 6 6 2
Indoor Environmental Quality	Mechanical Equipment Window Lighting Fixture	6+ 2 3
Innovation and Design	—	—

A summary of the Revit BIM element counts in evaluating LEED NC 2.1 credits is shown in Table 3-10. Entries are based on the gap analysis work done for Autodesk Sustainable BIM Project (Krishnamurti, Biswas, & Wang, 2010). Revit objects account for 10% of the requirements; 56% of the requirements can be specified by extending existing Revit families. Of the total required credits, 33% have to be supported through external databases, references or other information.

Table 3-10 Summary of Revit BIM element requirements

LEED NC 2.1	**Revit BIM element**	**Extension**	**Missing**
Sustainable Sites	10	12	19
Water Efficiency	2	5	14
Energy and Atmosphere	5	0	22

Materials and Resources	14	106	1
Indoor Environmental Quality	4	1	21
Innovation and Design	0	0	1
Subtotal	25	134	78
Percentage of Total (237)	**10%**	**56%**	**33%**

3.4.2 Information Augmentation for COBie

"COBie data is created by designers and expanded by contractors using a variety of software solutions."
(East B. , 2014)

The COBie model is a relational database of specific building information for the purposes of supporting the operation, maintenance and management of facility assets. The COBie model contains no geometry and represents only a subset of the building model—it is also referred to as a *lightweight* building information model.

COBie data starts with a listing of *facilities* (i.e. buildings or projects), each of which have *floors*, which within each are *spaces*, typically rooms in the interior and functional spaces in the exterior, such as "parking lot" or "patio seating." Each instance in a *space* also belongs to a *zone*. For spaces to perform as intended specific *systems* are made up of *components*. The *types* of systems include: electrical, heating, ventilating and air conditioning (HVAC), potable water, wastewater, fire protection, intrusion detection and alarms and other systems. Components and types are specified during design, installation or build. *Attribute* contains additional parameters of objects in other sheets *(facility, space, type, component etc.)*. All the above-mentioned sheets are generally used from early design to detail design phases. *Document* is used through out the design process. *Spare*, *Resource* and *Job* are for operation and maintenance.

The COBie data structure is examined as the open sources format for information augmentation and exchange. A COBie data structure, modified for sustainability assessment, referred to as 'COBie Plus', is a relational model based on a COBie model, which has been augmented with relevant information. Figure 3-17 illustrates the differences between a COBie and COBie+ data model. The left side illustrates the structure of building information in COBie. The right side indicates the augmentation required by sustainability assessment, in particular, the LEED sustainable building rating criteria.

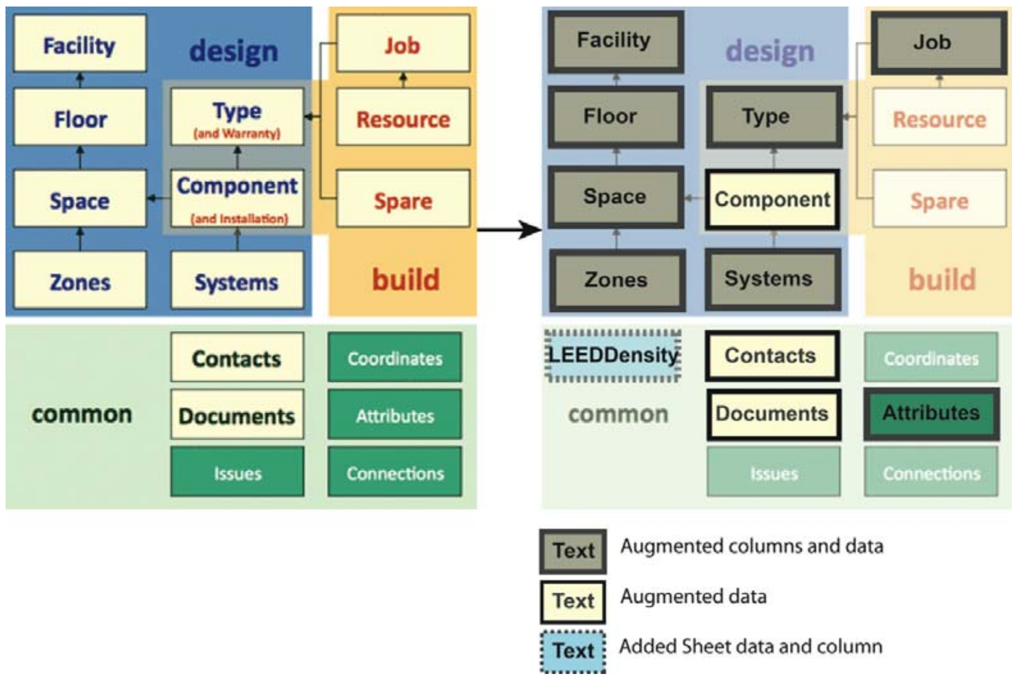
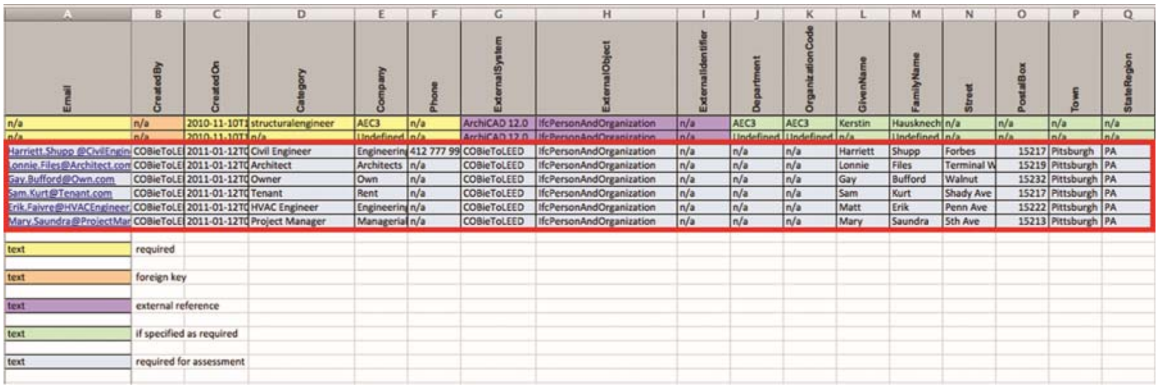


Figure 3-17 From COBie to COBie+: Illustrating augmentation of COBie for LEED
(Source for the left side: [(East B. , 2014): Figure 5])

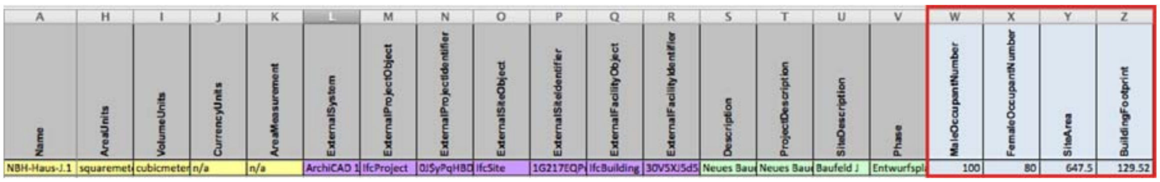
For the augmented model, COBie+, a new sheet, LEEDDensity, is added to the database. Sheets named Floor, Contacts, Component, and Documents retain their original columns but contains rows with additional data. The COBie data model is formatted as a color-coded spreadsheet (Section 2.3.2). Figure 3-18 shows the Contact sheet with original data, which is color-coded to reflect if the information is 'required', has a 'foreign key', has 'external reference', and is specified 'as required' and 'required for assessment'. To identify additional rows necessary for assessment, the cells are given a light blue background (Figure 3-18). For example in the Contacts sheet, LEED assessment requires the name of the 'Architect', 'Civil Engineer', 'Contractor', 'Commissioning Agent' in order to fulfill credit evaluation—these are the added rows; it is essential for the user to be aware of this particular element that needs to be filled with the appropriate information. Sheets named Attributes, Facility, Type, Space, Systems, and Job have additional columns with new fields and rows of additional data. Example of Facility sheet with added column is shown in Figure 3-19.



A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Email	CreatedBy	CreatedOn	Category	Company	Phone	ExternalSystem	ExternalObject	ExternalIdentifier	Department	OrganizationCode	GivenName	FamilyName	Street	PostalBox	Town	StateRegion
n/a	n/a	2010-11-10T1	structuralengineer	AEC3	n/a	ArchiCAD 12.0	IfcPersonAndOrganization	n/a	AEC3	AEC3	Kerstin	Hausknech	n/a	n/a	n/a	n/a
n/a	n/a	2010-11-10T1	n/a	Undefined	n/a	ArchiCAD 12.0	IfcPersonAndOrganization	n/a	Undefined	Undefined	n/a	Undefined	n/a	n/a	n/a	n/a
Harriett.Shupp @CivilEngin	COBieToLEI	2011-01-12T0	Civil Engineer	Engineerin	412 777 99	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Harriett	Shupp	Forbes	15217	Pitsburgh	PA
Lonnie.Files@Architect.com	COBieToLEI	2011-01-12T0	Architect	Architects	n/a	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Lonnie	Files	Terminal W	15219	Pittsburgh	PA
Gay.Bufford@Own.com	COBieToLEI	2011-01-12T0	Owner	Own	n/a	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Gay	Bufford	Walnut	15232	Pittsburgh	PA
Sam.Kurt@Tenant.com	COBieToLEI	2011-01-12T0	Tenant	Rent	n/a	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Sam	Kurt	Shady Ave	15217	Pittsburgh	PA
Erik.Faivre@HVACEngineer	COBieToLEI	2011-01-12T0	HVAC Engineer	Engineerin	n/a	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Matt	Erik	Penn Ave	15222	Pittsburgh	PA
Mary.Saundra@ProjectMar	COBieToLEI	2011-01-12T0	Project Manager	Managerial	n/a	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Mary	Saundra	5th Ave	15213	Pittsburgh	PA

text	required
text	foreign key
text	external reference
text	if specified as required
text	required for assessment

Figure 3-18 COBie Contact sheet with legend and added rows



A	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Name	AreaUnits	VolumeUnits	CurrencyUnits	AreaMeasurement	ExternalSystem	ExternalProjectObject	ExternalProjectIdentifier	ExternalSiteObject	ExternalSiteIdentifier	ExternalFacilityObject	ExternalFacilityIdentifier	Description	ProjectDescription	SiteDescription	Phase	MaleOccupantNumber	FemaleOccupantNumber	SiteArea	BuildingFootprint
NBH-Haus-J.1	squaremet	cubicmeter	n/a	n/a	ArchiCAD 1	IfcProject	0J$yPqHBD	IfcSite	1G217EQP	IfcBuilding	30VSXJ5d5	Neues Bau	Neues Bau	Baufeld J	Entwurfspl	100	80	647.5	129.52

Figure 3-19 COBie Facility sheet with added column

A summary of the IFC entities that has been mapped to the framework database by LEED categories is shown in Table 3-11. It can be seen that the IFC entities represent most of the Revit BIM elements in Table 3-9; these entities are also the subset of IFC entities that are represented in COBie.

Table 3-11 IFC Entities Used in LEED Assessments

LEED Category	COBie External Objects by IFC Entity	Minimum Number of Property Extensions
Sustainable Site	IfcLightFixtureType IfcObject IfcPersonAndOrganization IfcBuilding IfcSite IfcDocument	2 — 4 — 9 —
Water Efficiency	IfcSanitaryTerminalType	3
Energy and Atmosphere	IfcSystem IfcLightFixtureType IfcSpace	6+ 3 4
Material and Resources	IfcCeiling	6

LEED Category	COBie External Objects by IFC Entity	Minimum Number of Property Extensions
	IfcColumn	6
	IfcBeam	4
	IfcDoor	6
	IfcFloor	6
	IfcFurniture	6
	IfcRoof	6+
	IfcStair	6
	IfcStructuralItem	6
	IfcWall	6
	IfcWindow	2
Indoor Environmental Quality	IfcSystem	6+
	IfcWindow	2
	IfcLightFixtureType	3
Innovation and Design	—	—

3.4.3 Information Integration for Assessment

Figure 3-20 illustrates the flow of information in the sustainability framework, integrating rating systems with a building information model. For assessment information, credit elements are mapped to BIM elements using methods described in Sections 3.2 and 3.3. Assessment information for rating system elements is determined by assessment requirements and assessment data. The latter comprises BIM, performance and external data. This may necessitate augmenting the building information model by defining additional BIM elements possibly accommodating any required data in external databases.

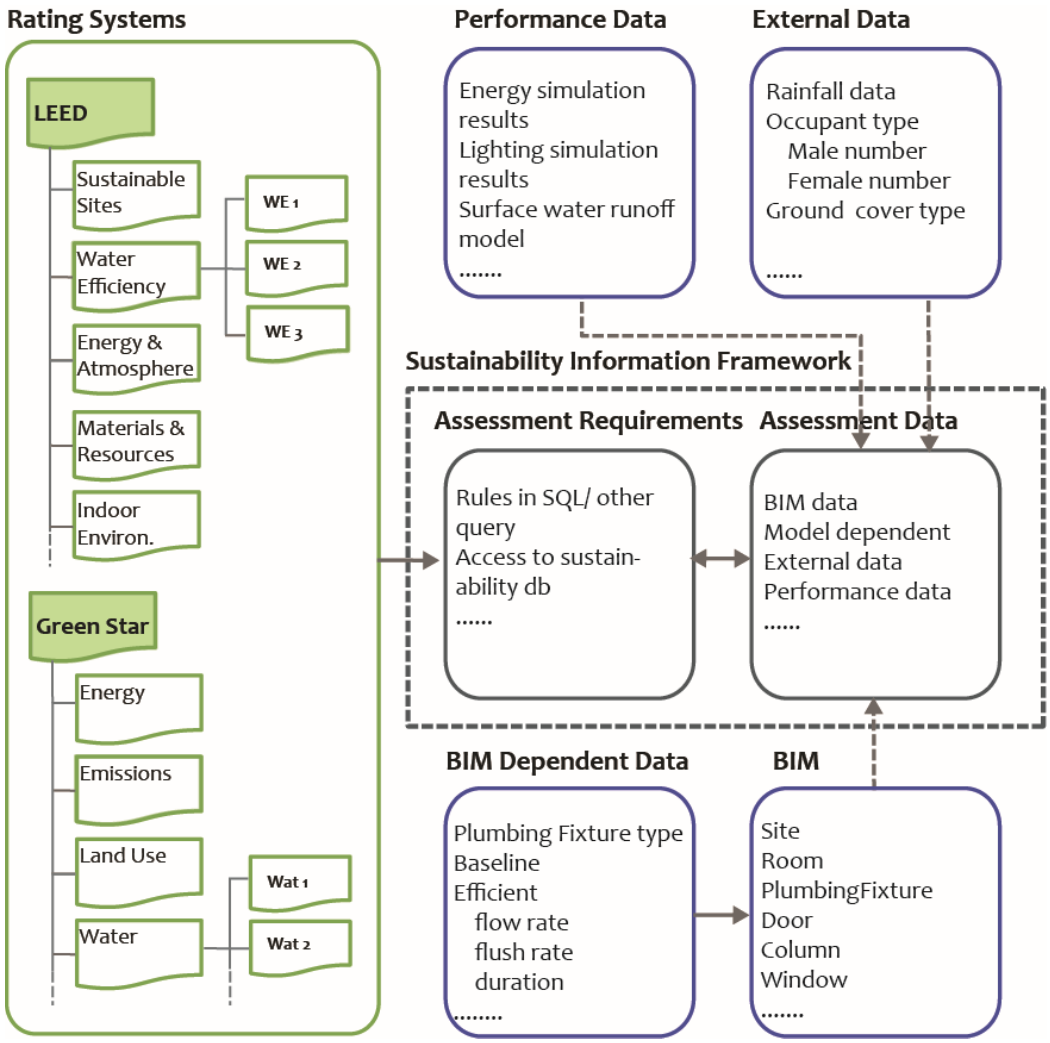


Figure 3-20 General sustainability information framework

The general list of categories for the rating systems is shown in Chapter 2: Table 2-4. Model dependent data is data inherently integral to the building information model such as necessary BIM element attributes that are currently not defined in the model. Examples of such are: occupancy data, custom attributes of BIM elements such as type of material, plumbing fixture flow rates, and so on. External data is often not a part of the model, but is needed for assessment. Examples of external data are rainfall data, type of vegetation and their evapotranspiration rates, water runoff coefficients for different ground cover types etc. Performance data are generated by specific tools, which are uniformly data oriented, objective and, mostly, adhere to formal standards and guidelines such as ISO, ASTM, or ASHRAE (Trusty, 2000). The US Department of Energy's Office of Energy Efficiency and Renewable Energy maintains an extensive directory of building software for generating performance related data, namely, tools for evaluating energy efficiency, renewable energy, and sustainability in buildings (US Department of Energy, 2011). Figure 3-21 shows an example of the information required for evaluating LEED 2.1 WEc3 (Reduce Water Use) within the proposed framework.

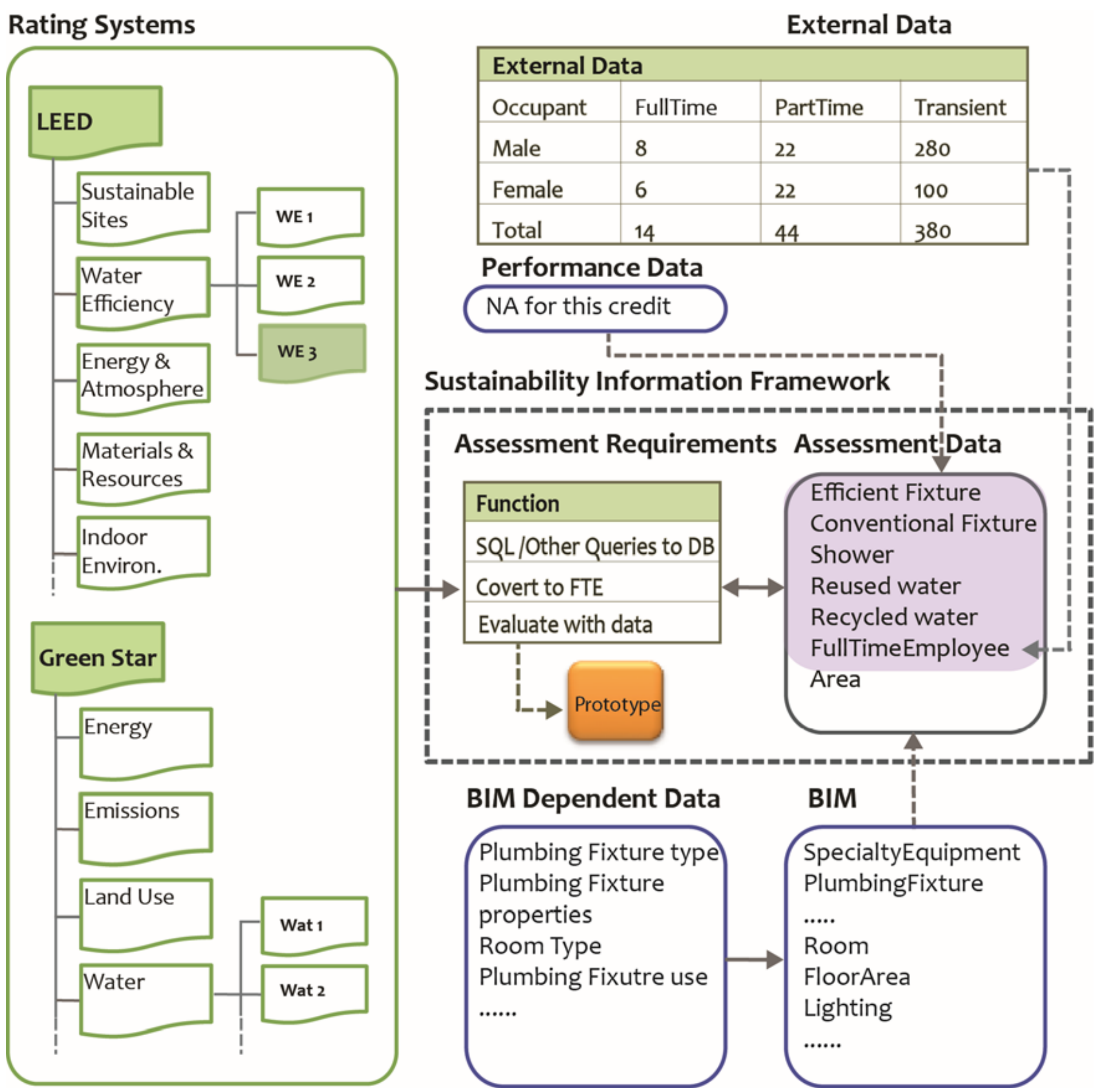


Figure 3-21 Information framework showing LEED 2.1 WE3 requirements

The elements are mapped to available BIM elements, checked for available attributes and augmented or supplemented as required. In order to evaluate LEED 2.1 Water Efficiency credit 3 (Reduce Indoor Water Use), the following information is required: number of male and female users, type of users – full time or part time; the type and number of plumbing fixtures, type of plumbing fixtures with flow rate, use numbers by male and females, recycled water use quantity etc. Plumbing fixtures are under ‘Plumbing Fixture’ in a BIM and may need to be customized with the attributes such as flow rate, flush rate, duration etc. Occupant number can be stored in a BIM project or may be in an external database with other information. The rules are interpreted by queries and functions that aggregate the information from the model and are visualized through the prototype application described in Chapter 4. The extent of automating pre-certification depends on the availability of required information for assessments.

3.5 Summary

In order to facilitate a process where integrated computer aided design for green buildings is viable, it is essential to be able to identify, and represent, building objects and their parameters. The informational needs required in the evaluation of the performance of a design from the various metrics for sustainability are presented in this chapter. The information organization structure created is followed by the information requirements from the analysis of several rating systems. Aggregated informational requirements are called ‘credit elements’, which are then mapped to a BIM for determining the general need to support sustainable building assessment. Selected rating systems show analysis of the credit elements according to number of uses. Availability of these ‘credit elements’ in BIM software both proprietary and non proprietary formats are discussed.

The changes in the ‘credit elements’ in the database created for providing the assessment data in the framework has changed over the evolutions of LEED. Three key versions of the database have been captured to analyse changes in the ‘credit element’ over the period of the research. The key versions of the database are taken from December 2010, 2012 and 2014. The 2012 and 2014 versions show total number of credit elements. The changes occurred by adding new credit elements to the previous version.

Table 3-12 Summary of changes in framework database over versions

Categories	Version 2010	Version 2012	Version 2014
A_1 Decision Making	3	6	29
B_1 Site	8	100	110
B_2 Building	20	84	145
B_4 Indoor Environment	17	62	83
B_5 Energy	3	12*	27**
B_6 Water	3	22	37

B_7 Emissions	5	20	21
C_1 Pre construction	10	13	24
D_1 Construction	6	6	16
D_2 Commissioning and Handover	3	13	24
E_1 Operation	7	7	8
F_1 Source and Disposal	3	3	3

* Additional 330 credit elements required for simulation from energy plus

** Additional 565 credit elements required for simulation from energy plus

The research establishes the informational requirements, specifies a general framework, and approach using information from commercial BIM software for sustainability assessment. The limitations in information identification, representation and mapping to rating systems primarily LEED NC 2.1 and later LEED 2009 requirements arise from commercial building information modelling tools and exchange formats during the period of the study.

Chapter 4

Sustainability assessment support

Figure 4-1 illustrates the workflow to provide information support for pre-assessment during the design phase. It is based on the sustainability information framework discussed in Chapter 3 Section 3.4.3. There are three tasks to creating a prototype for sustainable design pre assessment: template creation; rule formulation; and sustainability assessment. LEED 2.1 is the primary rating system chosen. Selected credits for LEED version 2009 and v4 are also tested.

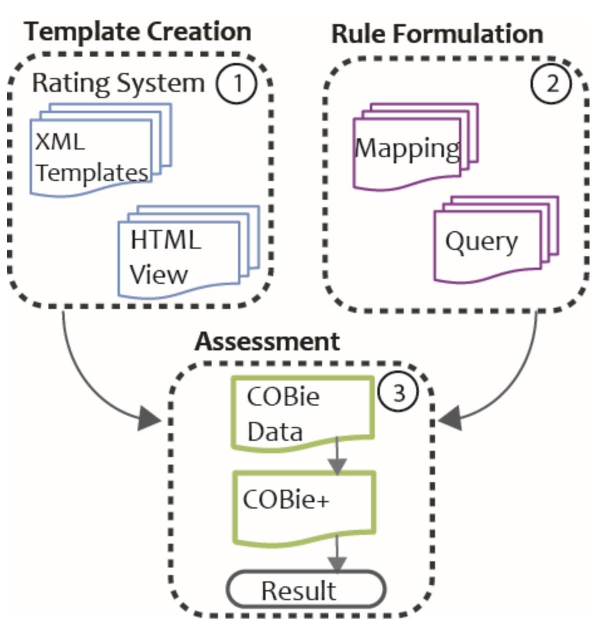


Figure 4-1 Three tasks to supporting sustainable design pre assessment

Template Creation

The first task is to develop the necessary XML templates to be filled by data from the COBie model. In this respect, all LEED 2.1 credits in all categories, and selected credits in LEED NC 2009 and LEED v4 HTML files were created via XSLT transformations of the XML templates.

Rule Formulation

The second task is the formulation of assessment rules. For this the data required for LEED evaluation is identified from the database and a mapping file is specified between LEED queries and fillable fields in the XML templates. For each LEED credit, conversion rules are stored as spreadsheet functions. Currently, mapping and LEED rules have been defined for all categories in LEED 2.1, selected credits in LEED 2009 (Water Efficiency and Energy and Atmosphere) categories, and demonstrated for Water Efficiency credit (Water use reduction), and Energy and Atmosphere credit EAp2 (Minimum energy performance) in LEED v4.

Sustainability Assessment

The last task is the development of a prototype application for sustainability assessment. It comprises a parser, rule calculator and template viewer. The prototype takes as input, a COBie model file, the assessment rules, a LEED XML template, and generates as output a submission-ready LEED HTML document. The user can manually edit, input data and rerun the application to update changes and save the files.

4.1 Case Studies

The prototype was tested on the following case studies.

4.1.1 Duplex Apartment Building

The first case study is a building model provided by the US Army's Construction Engineering Research Laboratory (CERL). It was used to test the development of the prototype application. The project is a residential duplex building (Figure 4-2). Information regarding site or surrounding structures are not available for the project. The model was created in Revit Architecture and a converted COBie file was provided. The file contained information from the design development phase of the project. The level of development (LOD)[21] provided can be classified at LOD 200 as per the American institute of architects (AIA (b), 2008), thus it contained information such as site and floor area; component, type and attributes of wall, floor, window, door, and fixtures.

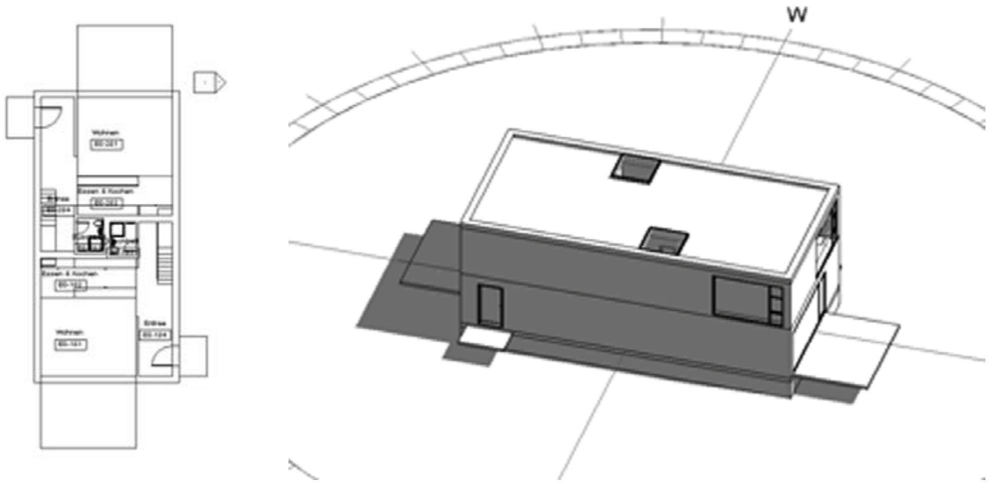


Figure 4-2 Case study from CERL (residential model)

4.1.2 407 South Craig Street

The second case study is a LEED 2.1 silver certified office building. See Figure 4-3, and Figure 4-4. The case study was modeled in Revit (Figure 4-5). New elements specifically pertaining to sustainability considerations, for example, solar panels, bicycle racks, plumbing fixtures and recycle bins were entered in the model. Revit caters for buildings elements to be part of a new construction or a renovation using the 'phase created' property. [22] For this case study, the phase created property of walls, floors, and roofs were set to 'existing'. By doing so, we are able to retrieve information to calculate the percentage of new versus existing material quantities. This calculation is relevant to the two rating systems explored in this case study, LEED and Green Star. To calculate site density, the surrounding neighborhood within a required density radius was mass modeled of appropriate heights.

[21] The term called LOD stands for level of development; there are 5 different levels which has been classified by the American institute of architects in a document called BIM Protocol (E202) however this document was created in 2008 and is still a sample paper and is very board
[22] Element property can be set to either 'new construction' or 'existing' in Revit.

Figure 4-3 407 S Craig Street view

Figure 4-4 407 S Craig St, solar panels (left), floor plan (right)

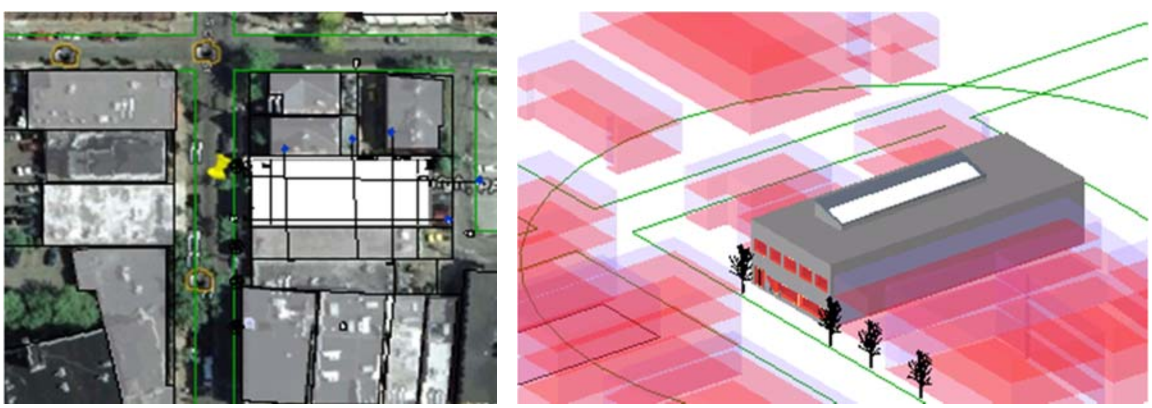


Figure 4-5 407 S Craig St, site plan and massing (left), 3D view (right)

Both the models were exported to IFC, and then converted into COBie using Bimservices (AEC 3, 2012) for use with the prototype. It should be noted that custom parameters that were created to hold properties such as material recycled content, responsibly sourced or certified wood neither showed up in the exported database nor in the converted COBie file. Additional fields have been created to hold these material attributes in the extended COBie structure. These additional attributes and elements necessary for assessment have been specified in the database (Section 3.3 and Appendix A)

4.2 Implementation

Figure 4-6 shows the process, and tasks employed in this research, for information exchange from an IFC building information model to a COBie+ data structure, to fill LEED evaluation templates. The source application, a proprietary BIM software, exports its building model to an IFC file. The IFC model is then converted to the COBie data structure via data exchange software—for demonstration, BimServices (AEC 3, 2012) was used. The COBie data structure is then extended as COBie+ to accommodate LEED requirements.

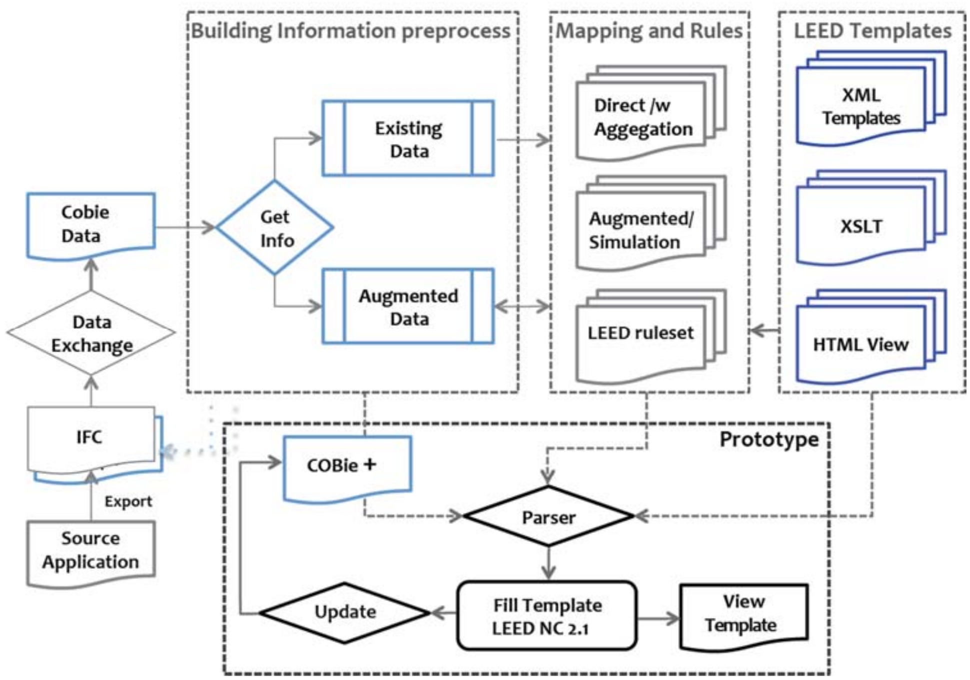


Figure 4-6 Sustainability assessment support prototype modules

Schematically, the prototype tool is implemented as modules (Figure 4-6) based on the above tasks. The modules comprise LEED Templates, Rules and Mapping files and the main parser, which is used in the prototype application presented in the section below.

4.2.1 Creation of LEED Templates

Templates for all six categories (Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Air Quality and Innovations in Design) for LEED 2.1 and LEED 2009 have been created following the process:

- First, xml files for each/multiple credit/s are created.
- Second, xsl style sheet is created to format the xml files.
- Third, XSLT is used to transform the xml documents to html format. (Figure 4-7)

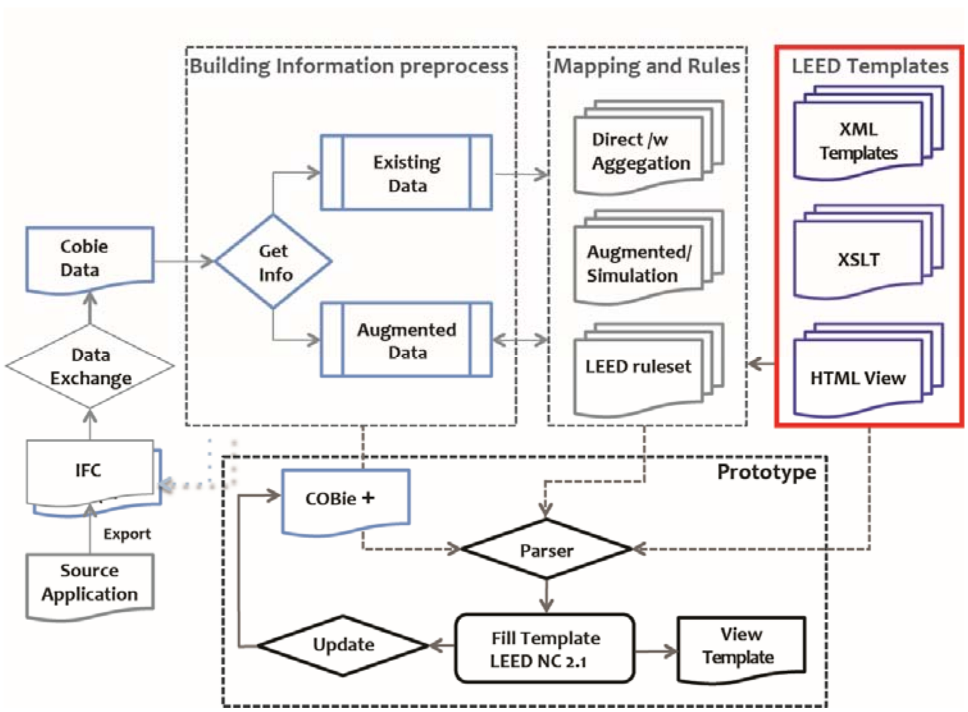


Figure 4-7 LEED template creation for pre-assessment support

This process of creating and converting XML templates provided a quick way for replicating LEED online templates to demonstrate the functionality of the prototype. This is described in Section 4.2.3. The summary of the templates is shown in Table 4-1 and Table 4-2 for LEED 2.1 and LEED 2009. The number of LEED submission templates may be different than the total number of LEED credits as a template may have more than a single credit, for example, Energy and Atmosphere credits EA 1.1 through 1.10 is documented within a single template. The templates column shows a breakdown of pre requisite and other attainable credits.

Table 4-1 LEED 2.1 Template List

LEED Category		**Number of Credits**	**Number of Templates**	
SS:	Sustainable Site	15	15	(1+14)
WE:	Water Efficiency	5	4	
EA:	Energy and Atmosphere	18	9	(3+6)
MR:	Materials and Resources	15	8	(1+7)
EQ:	Indoor Environmental Quality	17	11	(2+9)
ID:	Innovations in Design	5	2	
	Total Number	**76**	**49**	

Table 4-2 LEED 2009 Template List

LEED Category		**Number of Credits**	**Number of Templates**	
SS:	Sustainable Site	26	15	(1+14)
WE:	Water Efficiency	10	4	(1+ 3)
EA:	Energy and Atmosphere	35	9	(3+6)
MR:	Materials and Resources	14	9	(1+8)
EQ:	Indoor Environmental Quality	15	17	(2+15)
ID:	Innovations in Design	6	2	
RP:	Regional Priority	4	4	
	Total Number	**110**	**60**	

Sample LEED 2.1 templates for the Water Efficiency category, WE credit 3 (Water use reduction) are shown in their PDF, HTML, and XML formats in Figure 4-8, Figure 4-9, and Figure 4-10. The XML templates follow the layout of the original templates. The XML data structure is adopted due to its extensibility and the ability to exchange and aggregate a wide variety of data on the web (W3C (a), 2013). To view the template online, HTML files are created via XSLT transformations of the LEEDXML document.

LEED-NC

LEED FOR NEW CONSTRUCTION

LEED-NC 2.1 Letter Template
WE Credit 3: Water Use Reduction

SAMPLE FORM

(Civil Engineer or Responsible Party)

I, ____________, declare to USGBC that the project uses at least 20% less water than baseline fixture performance requirements of the Energy Policy Act of 1992.

Flow Fixture Chart

Flow Fixture Type	Water Use [GPF]	Duration [sec]
Conventional Lavatory	2.50	15
Low-Flow Lavatory	1.80	15
Kitchen Sink	2.50	15
Low-Flow Kitchen Sink	1.80	15
Shower	2.50	300
Low-Flow Shower	1.80	300

Flush Fixture Chart

Flush Fixture Type	Water Use [GPF]
Conventional Water Closet	1.60
Low-Flow Water Closet	1.10
Ultra Low-Flow Water Closet	0.80
Composting Toilet	0.00
Conventional Urinal	1.00
Waterless Urinal	0.00

Figure 4-8 LEED 2.1 Water Efficiency credit 3 PDF interactive template sample

WE Credit 3: Water Use Reduction

I, (Tenant, Project Manager, HVAC Engineer, Civil Engineer or Responsible party), John , declare that the project uses as least 20% less water than baseline fixture performance requirements of the Energy Policy Act of 1992

Flow Fixture Type	Water Use [gpm]	Duration[sec]
Conventional Lavatory	2.5	15
Low-Flow Lavatory	1.8	15
Kitchen Sink	2.5	15
Low-Flow Kitchen Sink	1.8	15
Shower	2.5	300
Low-Flow Shower	1.8	300
Janitor Sink	2.5	15

Flush Fixture Type	Water Use [gpf]
Conventional Water Closet	1.6
Low Flow Water Closet	1.1
Ultra Low-Flow Water Closet	0.8
Composting Toilet	0.0
Conventional Urinal	1.0
Waterless Urinal	0.0

Figure 4-9 LEED 2.1 Water Efficiency credit 3 in HTML format sample

For this particular credit, LEED 2.1 WE3 a minimum of seventy fields needs to be entered or filled for assessment. Each field in the template that needs to be filled is tagged with a unique ID (Figure 4-10). The IDs correspond to the HTML template shown in Figure 4-9, and is mapped with the query formulated to retrieve the information from the COBie data structure. The mapping is discussed in section 4.2.4.

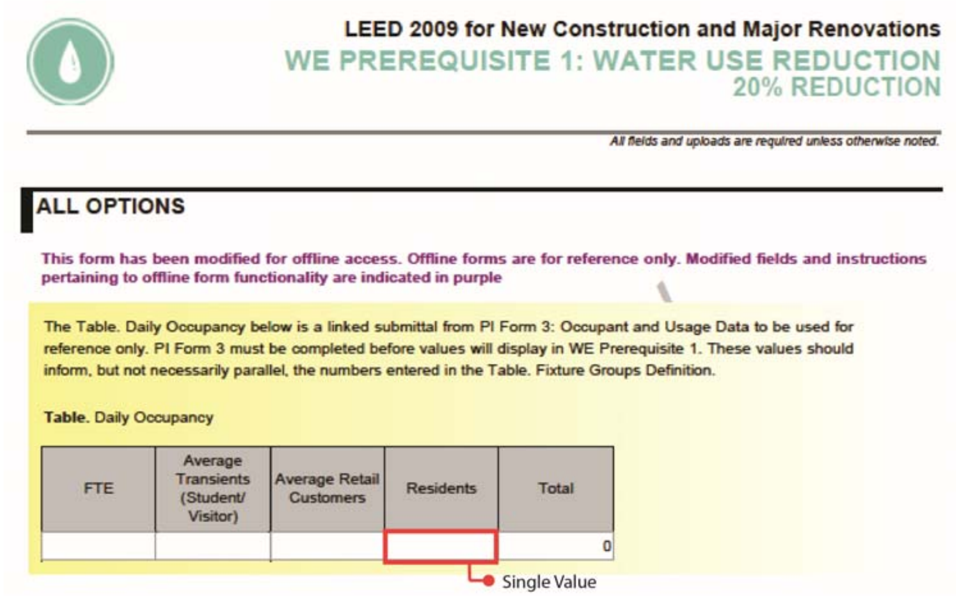
```
<LEED>
    <CreditName> WE Credit 3: Water Use Reduction</CreditName>
    <Contact1>
        <SentenceStart>I, </SentenceStart>
        <ContactRole>(Tenant, Project Manager, HVAC Engineer, Civil Engineer or Responsible party), </ContactRole>
        <Name id ="LEEDWE-0085">John </Name>   Field tagged for data
        <description>declare that the project uses as least 20% less water than baseline fixture performance
            requirements of the Energy Policy Act of 1992.
        </description>
    </Contact1>

    <WEc3Table1 id ="LFF">
        <FlowFixture>
            <Name>Conventional Lavatory</Name>
            <GPM id ="LEEDWE-0086">2.5</GPM>                 Field tagged for data
            <Duration id ="LEEDWE-0087">15</Duration>
        </FlowFixture>
        <FlowFixture>
            <Name>Low-Flow Lavatory</Name>
            <GPM id ="LEEDWE-0088">1.8</GPM>                 Field tagged for data
            <Duration id ="LEEDWE-0089">15</Duration>
        </FlowFixture>
        <FlowFixture>
            <Name>Kitchen Sink</Name>
            <GPM id ="LEEDWE-0090">2.5</GPM>                 Field tagged for data
            <Duration id ="LEEDWE-0091">15</Duration>
        </FlowFixture>
```

Figure 4-10 LEED 2.1 Water Efficiency credit 3 in XML format

PDF sample templates are shown in Figure 4-11, Figure 4-12 and Figure 4-13 for LEED 2009 WEp1 credit, Water Use Reduction. It should be noted that there is a change in the volume of information requirement as the versions are updated form LEED 2.1 to LEED 2009. For LEED 2009 WE credit 3, there are at least 78 data entry points that need to be filled for evaluating the credit. Analysis of total and new data required is discussed in Section 4.3. LEED 2009 XML templates were created using the same methods as LEED 2.1 XML templates. Details for mapping, rule creation and COBie data structure classification and augmentation are discussed in Section 4.2.2 and following sections. For this research, the types of fields that need to be filled are classified into three main kinds:

1) *Single value*: These fields are necessarily filled by one value, for example, 'First Name' in Figure 4-8, or 'Residents' in Figure 4-11. Such field values are mostly directly derived from the data model, or require preprocessing through aggregation or calculation.



LEED 2009 for New Construction and Major Renovations
WE PREREQUISITE 1: WATER USE REDUCTION
20% REDUCTION

All fields and uploads are required unless otherwise noted.

ALL OPTIONS

This form has been modified for offline access. Offline forms are for reference only. Modified fields and instructions pertaining to offline form functionality are indicated in purple

The Table. Daily Occupancy below is a linked submittal from PI Form 3: Occupant and Usage Data to be used for reference only. PI Form 3 must be completed before values will display in WE Prerequisite 1. These values should inform, but not necessarily parallel, the numbers entered in the Table. Fixture Groups Definition.

Table. Daily Occupancy

FTE	Average Transients (Student/ Visitor)	Average Retail Customers	Residents	Total
				0

Figure 4-11 LEED 2009 Water Use Reduction (WEp1), PDF Template, with single value

2) *Variable row values:* These occur in table rows–values vary according to the information in the model. For example in Figure 4-12 depending on the different plumbing fixtures used in the project, there can be one or more rows, each row containing multiple values. Each entry in a row has to be tagged and mapped so all the information can be aggregated to fill the table cells.

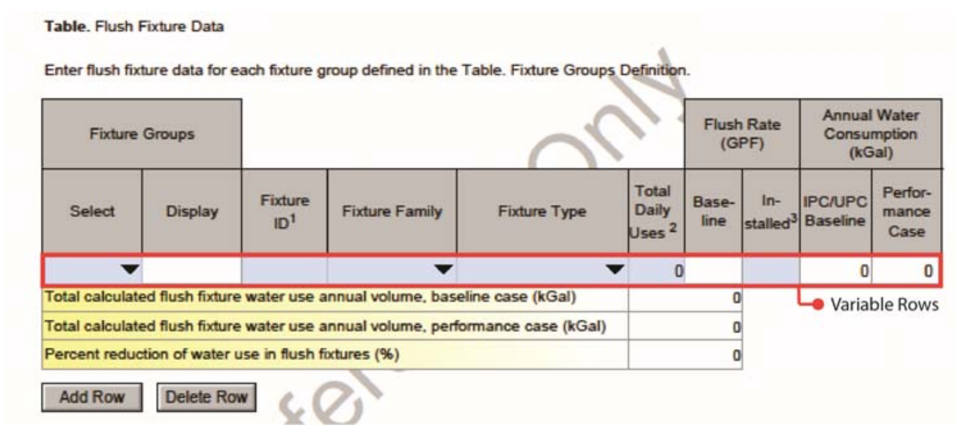


Table. Flush Fixture Data

Enter flush fixture data for each fixture group defined in the Table. Fixture Groups Definition.

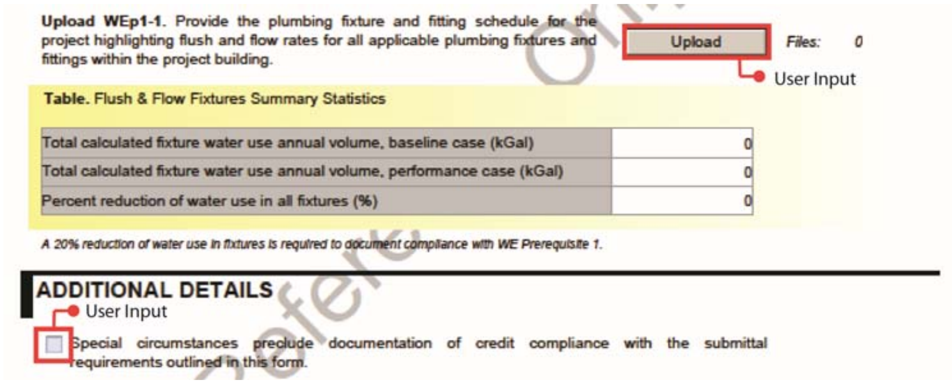
Fixture Groups						Flush Rate (GPF)		Annual Water Consumption (kGal)	
Select	Display	Fixture ID[1]	Fixture Family	Fixture Type	Total Daily Uses [2]	Base-line	In-stalled[3]	IPC/UPC Baseline	Perfor-mance Case
					0			0	0

Total calculated flush fixture water use annual volume, baseline case (kGal)	0
Total calculated flush fixture water use annual volume, performance case (kGal)	0
Percent reduction of water use in flush fixtures (%)	0

Figure 4-12 LEED 2009 Water Use Reduction (WEp1), PDF Template, with variable row

3) *User input*: This requires the user to upload a document or to select an option (Figure 4-13).

The focus is to capture information for the first two categories of data retrieval from the model.


Upload WEp1-1. Provide the plumbing fixture and fitting schedule for the project highlighting flush and flow rates for all applicable plumbing fixtures and fittings within the project building.

Upload — Files: 0

User Input

Table. Flush & Flow Fixtures Summary Statistics

Total calculated fixture water use annual volume, baseline case (kGal)	0
Total calculated fixture water use annual volume, performance case (kGal)	0
Percent reduction of water use in all fixtures (%)	0

A 20% reduction of water use in fixtures is required to document compliance with WE Prerequisite 1.

ADDITIONAL DETAILS

User Input

☐ Special circumstances preclude documentation of credit compliance with the submittal requirements outlined in this form.

Figure 4-13 LEED 2009 Water Use Reduction (WEp1), PDF Template with user input

4.2.2 Rule Creation

As presented earlier in Sections 2.3.1 and 2.3.2, prevalent design modeling tools currently support both IFC, and COBie schemas as data exchange formats, and these formats are extensible to represent information necessary for providing support for sustainable design pre assessment. Within this context, the choice of data format for prototyping a tool for this research is premised upon capability to demonstrate the concept of a sustainability information assessment support tool, ease of development and implementation. This includes extensibility to capture information comprehensively, ease of implementing extensions, prevalence in industry, and ability to demonstrate data availability and exchange between design modeling tools. The creation of rules involves mapping them to existing data in the model and identifying data that needs to be augmented (Figure 4-14).

The COBie data format is selected for use given the ease of legibility and extension when developing the developing the prototype. While extending COBie to COBie+ (Figure 4-15), it necessitates changes to some of the schema mentioned in Section 3.4.2. A summary of the change is given in

Table 4-3.

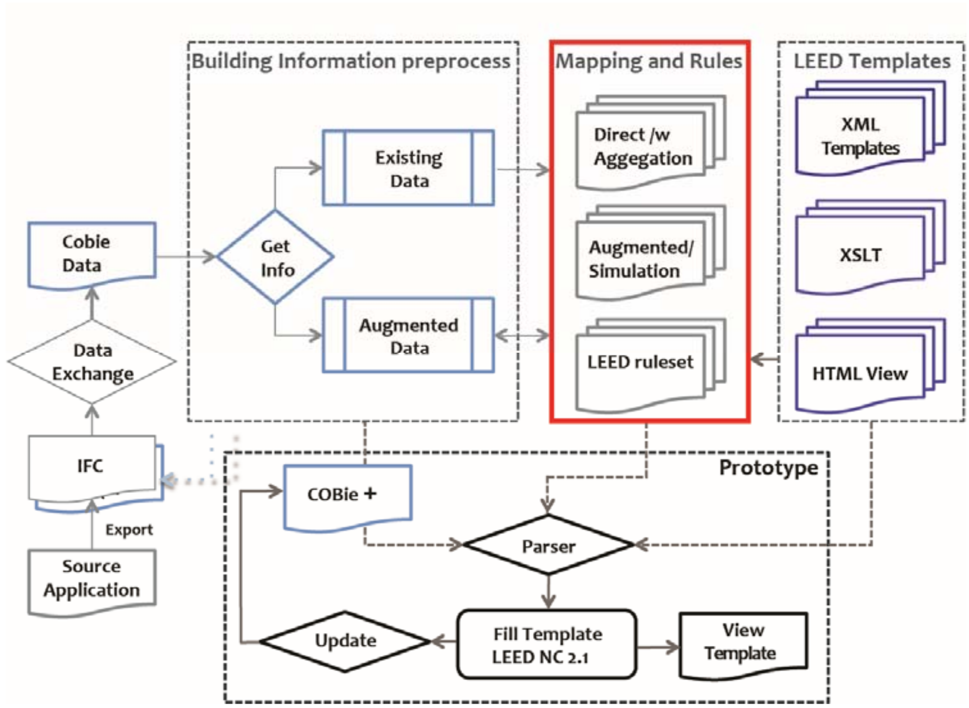


Figure 4-14 Mapping and rule creation for pre assessment support

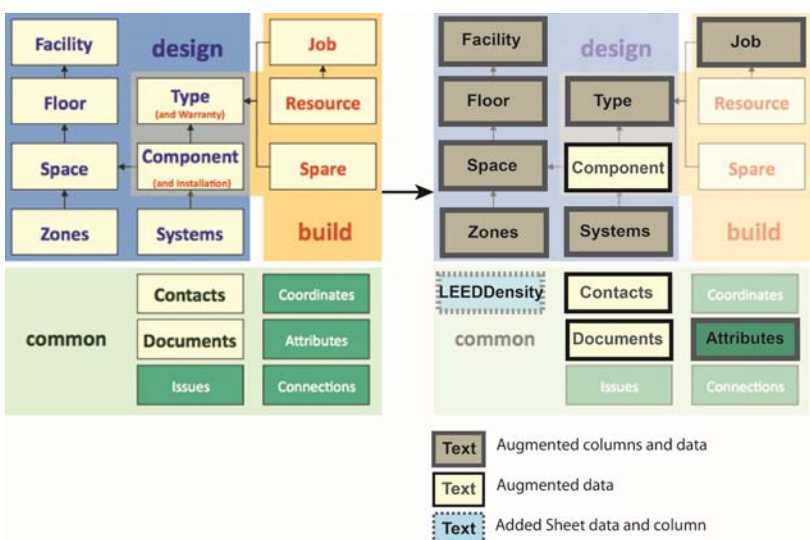


Figure 4-15 COBie to COBie+ data augmentation (Source for the left side: (East, COBie Structure, 2014))

Table 4-3 Summary of columns added to COBie sheets

Sheet Name	Column Name	Description
Facility	MaleOccupantNumber, FemaleOccupantNumber, SiteArea BuildingFootprint	Occupant number in each project is necessary. Male and female occupant numbers are further required for calculating water efficiency
Space	PerimeterOrNonperimeter OperableWindowNumber LightingControl TemperatureControl AirFlowControl	These are mainly used for calculating lighting, temperature, humidity, and airflow control within a space.
Zone	AirChangeEffectiveness Temperature Humidity Control	These properties are required for each zone and are values rather than controls so it seems to be the sheet to place them.
Type	Distance (ofManufacturer) Number PostConsumer PostIndustrial DistanceofHarvest Renewable Certified	These are all required for material calculations. Many Types of elements require the following attributes. We are trying to keep relevant information in one sheet for clarity and querying, however these can be added as attributes in the Attribute Sheet.
System	Value EnergyCategory, EnergyType, AnnualEnergyUse, AnnualEnergyCost	Energy information is not directly addressed as seen. We suggest that it could be an attribute of HVAC systems. These are still under review.
Job	End	This could also be represented by duration which is present as there is already
Document	Reference	We often look for type of document to be submitted for example drawing or narrative document. References to third party bodies or standards are represented in this column.
Total Number	**27**	

The extension of COBie is relatively easier to develop as compared to extending general purpose entities with defined base entity and relationship objects in the IFC schema. In addition, the availability of Java API for XML processing, allows ease of development and implementation of XML-based features within the new tool.

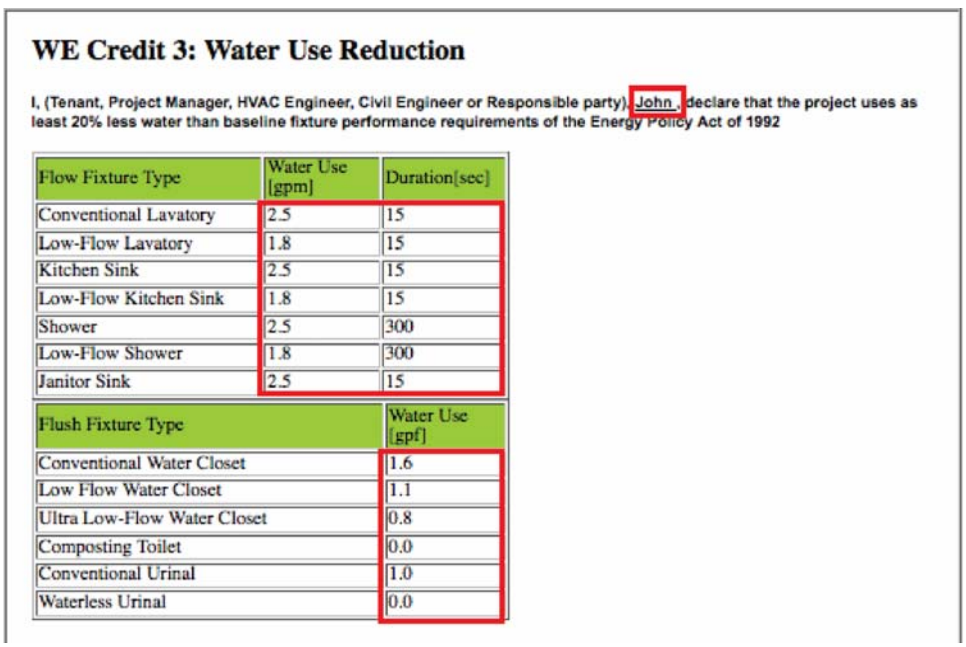
LEED Rule Conversion into Computable form

LEED requirements are subdivided and converted into executable rules. Table 4-4 illustrates representative sample rules for filling LEED 2.1 WE3 (Water Use Reduction) and data output from the case study model information.

Table 4-4 Sample LEED 2.1 rules for WE3 (Water Use Reduction)

ID	Type	Condition	Value	Output
WE-0085	Directw Aggregation	Contact.Category == CivilEngineer)	Contact.GivenName + Contact.FamilyName	John Doe
WE-0086	Direct	(Attribute.ExtObj == IfcSanitaryTerminalType) &&(Attribute.RowName == Conventional Lavatory) && (Attribute.Name ==FlowRate)	Attribute.Value	2.5
WE-0087	Direct	(Attribute.ExtObj == IfcSanitaryTerminalType) &&(Attribute.RowName == Conventional Lavatory) && (Attribute.Name ==Duration)	Attribute.Value	15
WE-0088	Direct	(Attribute.ExtObj == IfcSanitaryTerminalType) &&(Attribute.RowName == Low Flow Lavatory) && (Attribute.Name ==FlowRate)	Attribute.Value	1.8
WE-0089	Direct	(Attribute.ExtObj == IfcSanitaryTerminalType) &&(Attribute.RowName == Low Flow Lavatory) && (Attribute.Name ==Duration)	Attribute.Value	15
WE-0088	Direct	(Attribute.ExtObj == IfcSanitaryTerminalType) &&(Attribute.RowName == Kitchen Sink) && (Attribute.Name ==FlowRate)	Attribute.Value	2.5
WE-0089	Direct	(Attribute.ExtObj == IfcSanitaryTerminalType) &&(Attribute.RowName == Kitchen Sink) && (Attribute.Name == Duration)	Attribute.Value	15

The first column is the ID of the value retrieved or processed for use in other calculations. The second column specifies a Type, which indicates how the output value is determined. The classification of Types of data is given in the sequel (Section 4.2.3). The third column, Condition contains the main query from the COBie data structure. For example the first row in the table queries the COBie 'Contact' Sheet and column named 'Category' for 'Civil Engineer' and returns the value for 'GivenName' and 'FamilyName' in the Value column. Some values such as the 'Fixture Flow Rate' attribute is associated with 'IfcSanitaryFixture' are directly retrieved from the COBie Attribute sheet; others like the professional signature require aggregation (DirectwAggregation)—here two distinct string values from the data structure are concatenated. The output column shows the data retrieved from COBie. This type of 'Direct' data corresponds to the 'single value' data type shown in Figure 4-10 and Figure 4-11. A sample Html template is shown in Figure 4-16 with the single-valued data indicated.



WE Credit 3: Water Use Reduction

I, (Tenant, Project Manager, HVAC Engineer, Civil Engineer or Responsible party) John , declare that the project uses as least 20% less water than baseline fixture performance requirements of the Energy Policy Act of 1992

Flow Fixture Type	Water Use [gpm]	Duration[sec]
Conventional Lavatory	2.5	15
Low-Flow Lavatory	1.8	15
Kitchen Sink	2.5	15
Low-Flow Kitchen Sink	1.8	15
Shower	2.5	300
Low-Flow Shower	1.8	300
Janitor Sink	2.5	15

Flush Fixture Type	Water Use [gpf]
Conventional Water Closet	1.6
Low Flow Water Closet	1.1
Ultra Low-Flow Water Closet	0.8
Composting Toilet	0.0
Conventional Urinal	1.0
Waterless Urinal	0.0

Figure 4-16 LEED 2.1 WE3 template sample filled by values from Table 4-4

Other data types indicate basic arithmetic operations such as 'SUM' (summation), 'SUB' (subtraction), 'DIV' (division),'MUL' (multiplication), which are used to process values retrieved from the database (illustrated in Table 4-5 by example rules in the implementation of LEED 2009 WEp1 (Water Use Reduction). The columns named, Type, Condition and Value, are required by the prototype parser to implement the rules. An initial value is seen in the Output column; these values are propagated to update LEED submission templates, which are shown in Figure 4-17. Table 4-6 shows the output when there are variable row values, or a list of values as described in Section 4.2.1.

Table 4-5 LEED 2009 WEp1 Water use reduction with calculations

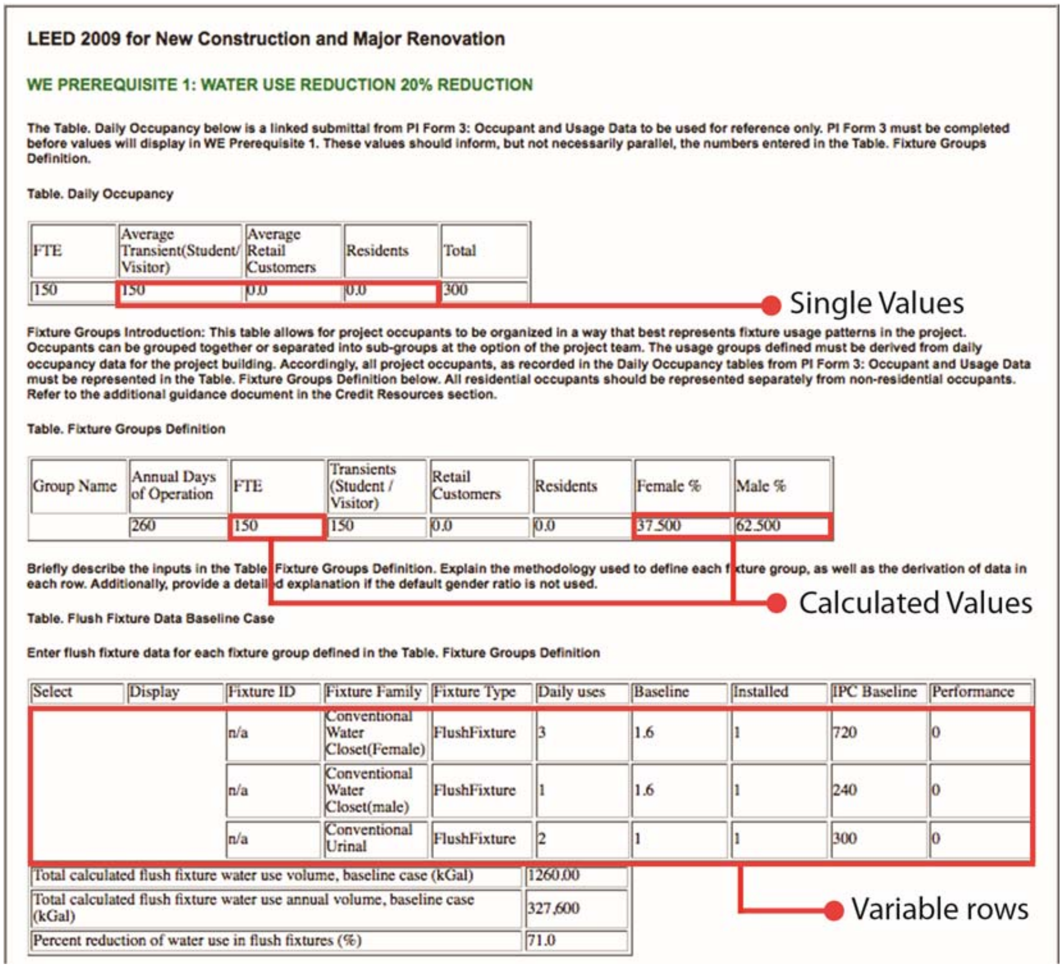
ID	Type	Condition	Value	Output
LEEDWE p1-0007	Direct	(Facility.ExternalFacility Object == IfcBuilding)	Facility.DaysUsed	260
LEEDWE p1-0007a	MUL		MUL (1, LEEDWEp1-0001)	150
LEEDWE p1-0008	Direct	Type.Name ==Transient	Type.Number	150
LEEDWE p1-0009	Direct	Type.Name ==Customer	Type.Number	0
LEEDWE p1-0010	Direct	Type.Name == Resident	Type.Number	0
LEEDWE p1-F014	Direct	(Facility.ExternalFacility Object == IfcBuilding)	Facility.FemaleOccupant Number	30
LEEDWE p1-F015	Direct	(Facility.ExternalFacility Object == IfcBuilding)	Facility.MaleOccupant Number	50
LEEDWE p1-F016	SUM	Null	SUM (LEEDWEp1-F014, LEEDWEp1-F015)	80.000
LEEDWE p1-F017	DIV	Null	DIV (LEEDWEp1-F014, LEEDWEp1-F016)	0.375
LEEDWE p1-0011	MUL	Null	MUL (LEEDWEp1-F017, 100)	37.500
LEEDWE p1-0012	SUB	Null	SUB (100, LEEDWEp1-0011)	62.500

Table 4-6 LEED 2009 WEp1 Water use reduction with variable rows

ID	Type	Condition	Value	Output
LEEDWE p1-0015	Direct	(Type.LEEDAttribute == FlushFixture) && (Type.Description == Baseline)	Type. ExtIdentifier	n/a | n/a | n/a

ID	Type	Condition	Value	Output
LEEDWE p1-0016	Direct	(Type.LEEDAttribute == FlushFixture) && (Type.Description == Baseline)	Type.Name	Conventional WaterCloset(Female) | Conventional WaterCloset(Male) | ConventaionalUrinal
LEEDWE p1-0017	Direct	(Type.LEEDAttribute == FlushFixture) && (Type.Description == Baseline)	Type. LEEDAttribute	FlushFixture | FlushFixture | FlushFixture
LEEDWE p1-0018	Direct	(Attribute.LEEDAttribute == FlushFixture) && (Attribute.Description == Baseline) && (Attribute.Name == TotalDailyUse)	Attribute.Value	3 | 1 | 2
LEEDWE p1-0019	Direct	(Attribute.LEEDAttribute == FlushFixture) && (Attribute.Description == Baseline) && (Attribute.Name == FlowRate)	Attribute.Value	1.6 | 1.6 | 1
LEEDWE p1-0020	Direct	(Attribute.LEEDAttribute == FlushFixture) && (Attribute.Description == Baseline) && (Attribute.Name == Duration)	Attribute.Value	1 | 1 | 1
LEEDWE p1-F019	MULL	Null	MULL (LEEDWEp1-0007a, LEEDWEp1-0018, LEEDWEp1-0019, LEEDWEp1-0020)	720 | 240 | 300

Note that the output may be single-valued, variable row-valued, or a list of values. For instance, the rows with id LEEDWEp1-0015 through LEEDWEp1-0020 retrieve a list of water fixtures; their uses number, flow rates etc. ID LEEDWEp1-F019 uses ‘MULL’ (multiplication of values in list) to process information by multiplying a list of single values aggregated in the previous steps. Figure 4-17 shows the values filled in Baseline Case Table section of the LEED 2009 WEp1 template. The extent of automating pre-certification depends on the availability of required information for assessments. It can be seen that some fields remain empty as values are missing. The empty template in original PDF form is shown previously in Figure 4-12.



LEED 2009 for New Construction and Major Renovation

WE PREREQUISITE 1: WATER USE REDUCTION 20% REDUCTION

The Table. Daily Occupancy below is a linked submittal from PI Form 3: Occupant and Usage Data to be used for reference only. PI Form 3 must be completed before values will display in WE Prerequisite 1. These values should inform, but not necessarily parallel, the numbers entered in the Table. Fixture Groups Definition.

Table. Daily Occupancy

FTE	Average Transient(Student/ Visitor)	Average Retail Customers	Residents	Total
150	150	0.0	0.0	300

Fixture Groups Introduction: This table allows for project occupants to be organized in a way that best represents fixture usage patterns in the project. Occupants can be grouped together or separated into sub-groups at the option of the project team. The usage groups defined must be derived from daily occupancy data for the project building. Accordingly, all project occupants, as recorded in the Daily Occupancy tables from PI Form 3: Occupant and Usage Data must be represented in the Table. Fixture Groups Definition below. All residential occupants should be represented separately from non-residential occupants. Refer to the additional guidance document in the Credit Resources section.

Table. Fixture Groups Definition

Group Name	Annual Days of Operation	FTE	Transients (Student / Visitor)	Retail Customers	Residents	Female %	Male %
	260	150	150	0.0	0.0	37.500	62.500

Briefly describe the inputs in the Table Fixture Groups Definition. Explain the methodology used to define each fixture group, as well as the derivation of data in each row. Additionally, provide a detailed explanation if the default gender ratio is not used.

Table. Flush Fixture Data Baseline Case

Enter flush fixture data for each fixture group defined in the Table. Fixture Groups Definition

Select	Display	Fixture ID	Fixture Family	Fixture Type	Daily uses	Baseline	Installed	IPC Baseline	Performance
		n/a	Conventional Water Closet(Female)	FlushFixture	3	1.6	1	720	0
		n/a	Conventional Water Closet(male)	FlushFixture	1	1.6	1	240	0
		n/a	Conventional Urinal	FlushFixture	2	1	1	300	0

Total calculated flush fixture water use volume, baseline case (kGal)	1260.00
Total calculated flush fixture water use annual volume, baseline case (kGal)	327,600
Percent reduction of water use in flush fixtures (%)	71.0

Figure 4-17 LEED 2009 WEp1 template sample filled by values from Table 4-6

LEED requirements are periodically revised and updated, and in the process, becoming increasingly more rigorous (USGBC (e), 2014). To cater for evolving requirements and rule sets required for assessments in a flexible manner, LEED requirements are stored as a set of executable rules in spreadsheets, which can be interpreted for assessment. Providing this functionality to an otherwise static set of hard coded rules allows the application to be potentially and more readily accommodate future rating requirement updates. It enables multi-disciplinary cooperation from sustainable assessment rule mapping to corresponding building data (and vice versa).

4.2.3 COBie Data Classification for Implementation

Data exported to COBie has been classified into three main types for implementing the prototype: Direct data, Direct with Aggregation and LEED Attribute.

1. Direct Data

In the mapping file *'Direct data'* (Figure 4-18) is COBie data that can be retrieved without manipulation. Figure Figure 4-19 shows 'direct' data being queried from the sheet named Contact and the column named'Category'.

G	H	I	J	K	L	M	N	O
LEEDDat	LEED	LEEDDataT	COBieSheet	COBieColumn	COBieInformatic	TypeForIn	COBieImplementationCondition	COBieImplementationValue
Single	Null	Null	Contact	FamilyName+	DirectwAggregat	DirectwA	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.GivenName + Contact.Family
List	SSp1	SEM	Document	SoilErosionMe	LEEDattribute	Direct	Document.Category == SoilErosionMeasure	Document.Name
List	SSp1	SEM	Document	SoilErosionMe	LEEDattribute	Direct	Document.Category == SoilErosionMeasure	Document.Reference
Single	Null	Null	Contact	FamilyName+	DirectwAggregat	DirectwA	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.GivenName + Contact.Family
List	SSp1	LOM	Document	ListOfMeasure	LEEDattribute	DirectwA	Document.Category == ListOfMeasure	Document.Name
List	SSp1	LOM	Document	ListOfMeasure	LEEDattribute	DirectwA	Document.Category == ListOfMeasure	Document.Reference
Single	Null	Null	Null	Null	LEEDvariable	LEEDvaria	Null	Null
Single	Null	Null	Contact	FamilyName+	Direct	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.GivenName + Contact.Family
Single	Null	Null	Contact	Company	Direct	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.Company
Single	Null	Null	Contact	Category	Direct	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.Category
Single	Null	Null	Contact	Null	LEEDvariable	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.Signature

Figure 4-18 COBie direct data classification for computable LEED rules

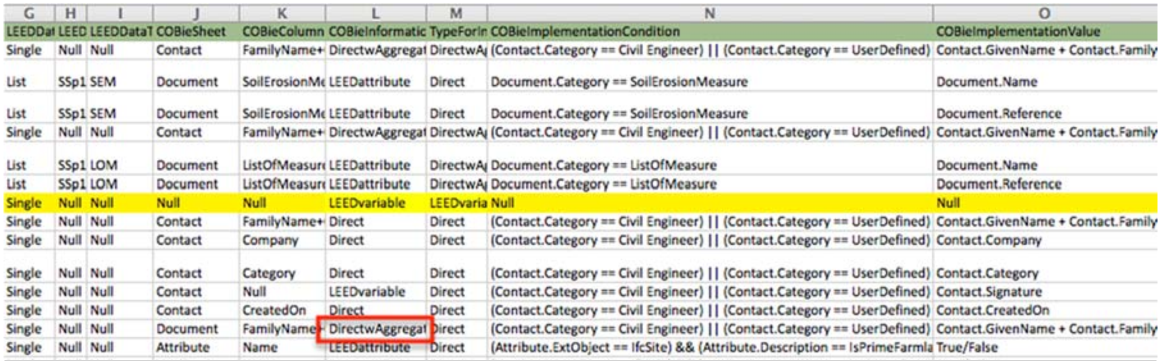
F19

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Email	CreatedBy	CreatedOn	Category	Company	Phone	ExternalSystem	ExternalObject	ExternalIdentifier	Department	OrganizationCode	GivenName	FamilyName	Street	PostalBox	Town	StateRegion	PostalCode	Country	Signature
2	n/a	n/a	2010-11-10T	structuralengineer	AEC3	n/a	ArchiCAD	IfcPersonAndOrg	n/a	AEC3	AEC3	Kerstin	Hausknech	n/a	n/a	n/a	n/a	n/a	n/a	n/a
3	n/a	n/a	2010-11-10T	n/a	Undefined	n/a	ArchiCAD	IfcPersonAndOrg	n/a	Undefined	Undefined	n/a	Undefined	n/a	n/a	n/a	n/a	n/a	n/a	n/a
4	n/a	cmu	11/11/10	Civil Engineer	xx	n/a	n/a	IfcPersonAndOrg	n/a	n/a	n/a	John	Doe	Forbes	n/a	Pitsburgh	n/a	15213	USA	John Doe
5	n/a	cmu	11/11/10	Architect	yy	n/a	n/a	IfcPersonAndOrg	n/a	n/a	n/a	Jane	Adams	Forbes	n/a	Pittsburgh	n/a	15213	USA	Jane Adams
6	n/a	cmu	11/12/10	Owner	n/a	n/a	n/a	IfcPersonAndOrg	n/a	n/a	n/a	Sam	Allan	Penn	n/a	Pittsburgh	n/a	15217	USA	Sam Allan
7	n/a	cmu	11/13/10	Tenant	n/a	n/a	n/a	IfcPersonAndOrg	n/a	n/a	n/a	Ann	Scott	Penn	n/a	Pittsburgh	n/a	15217	USA	Ann Scott
8	n/a	cmu	11/14/10	HVAC Engineer	zz	n/a	n/a	IfcPersonAndOrg	n/a	n/a	n/a	Bob	Parker	Penn	n/a	Pittsburgh	n/a	15217	USA	Bob Parker

Figure 4-19 *Direct* – 'Role of Professional' from 'Contact' sheet, 'Category' column

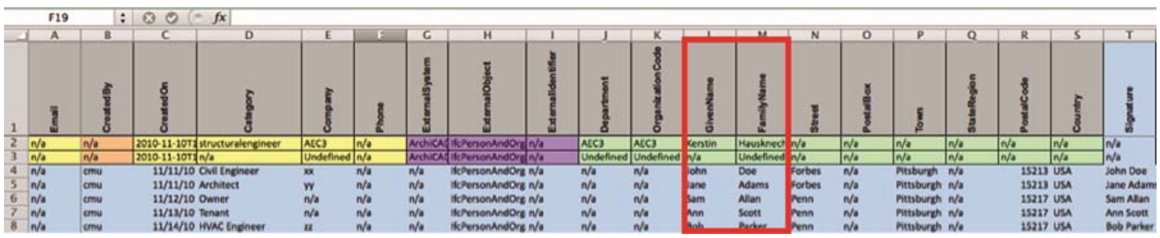
2. Direct with Aggregation

This type of data is referenced as '*DirectwAggregation*' (Figure 4-20). This indicates data that needs to be aggregated from multiple columns in the CObie data structure. In some cases data needs to be aggregated from multiple sheets and may need to be processed prior to being used in evaluating the rules. In Figure 4-21 values from sheet named Contact are aggregated from columns GivenName and FamilyName in order to retrieve the full name of person.



G	H	I	J	K	L	M	N	O
LEEDDat	LEED	LEEDDataT	COBieSheet	COBieColumn	COBieInformatic	TypeForIn	COBieImplementationCondition	COBieImplementationValue
Single	Null	Null	Contact	FamilyName+	DirectwAggregat	DirectwA	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.GivenName + Contact.Family
List	SSp1	SEM	Document	SoilErosionMe	LEEDattribute	Direct	Document.Category == SoilErosionMeasure	Document.Name
List	SSp1	SEM	Document	SoilErosionMe	LEEDattribute	Direct	Document.Category == SoilErosionMeasure	Document.Reference
Single	Null	Null	Contact	FamilyName+	DirectwAggregat	DirectwA	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.GivenName + Contact.Family
List	SSp1	LOM	Document	ListOfMeasure	LEEDattribute	DirectwA	Document.Category == ListOfMeasure	Document.Name
List	SSp1	LOM	Document	ListOfMeasure	LEEDattribute	DirectwA	Document.Category == ListOfMeasure	Document.Reference
Single	Null	Null	Null	Null	LEEDvariable	LEEDvaria	Null	Null
Single	Null	Null	Contact	FamilyName+	Direct	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.GivenName + Contact.Family
Single	Null	Null	Contact	Company	Direct	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.Company
Single	Null	Null	Contact	Category	Direct	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.Category
Single	Null	Null	Contact	Null	LEEDvariable	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.Signature
Single	Null	Null	Contact	CreatedOn	Direct	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.CreatedOn
Single	Null	Null	Document	FamilyName+	DirectwAggregat	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.GivenName + Contact.Family
Single	Null	Null	Attribute	Name	LEEDattribute	Direct	(Attribute.ExtObject == IfcSite) && (Attribute.Description == IsPrimeFarmla	True/False

Figure 4-20 COBie direct w aggregation data classification for computable LEED rules



F19

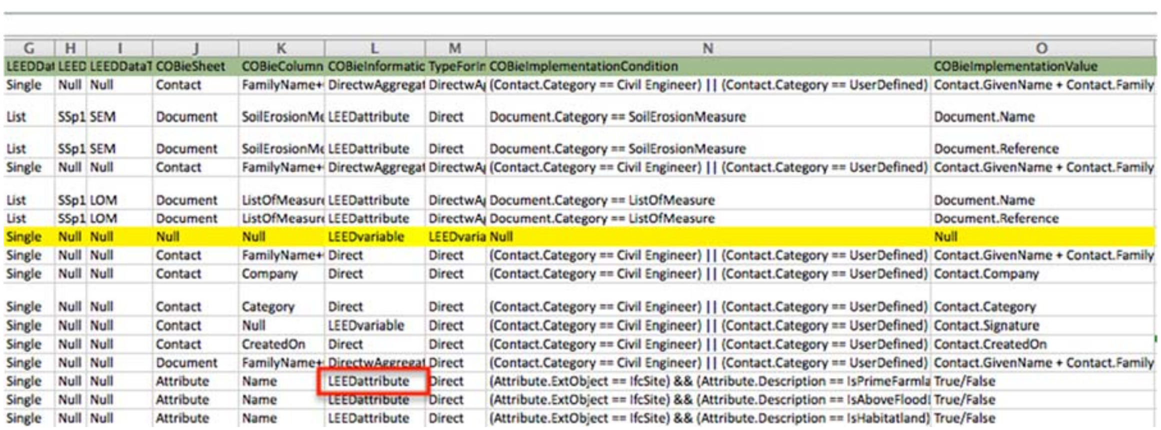
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Email	CreatedBy	CreatedOn	Category	Company	Phone	ExternalSystem	ExternalObject	ExternalIdentifier	Department	OrganizationCode	GivenName	FamilyName	Street	PostalBox	Town	StateRegion	PostalCode	Country	Signature
2	n/a	n/a	2010-11-10T1	structuralengineer	AEC3	n/a	ArchiCAD	IfcPersonAndOrg	n/a	AEC3	AEC3	Kerstin	Hausknecht	n/a	n/a	n/a	n/a	n/a	n/a	n/a
3	n/a	n/a	2010-11-10T1	n/a	Undefined	n/a	ArchiCAD	IfcPersonAndOrg	n/a	Undefined	Undefined	n/a	Undefined	n/a	n/a	n/a	n/a	n/a	n/a	n/a
4	n/a	cmu	11/11/10	Civil Engineer	xx	n/a	n/a	IfcPersonAndOrg	n/a	n/a	n/a	John	Doe	Forbes	n/a	Pittsburgh	n/a	15213	USA	John Doe
5	n/a	cmu	11/11/10	Architect	yy	n/a	n/a	IfcPersonAndOrg	n/a	n/a	n/a	Jane	Adams	Forbes	n/a	Pittsburgh	n/a	15213	USA	Jane Adam
6	n/a	cmu	11/12/10	Owner	n/a	n/a	n/a	IfcPersonAndOrg	n/a	n/a	n/a	Sam	Allan	Penn	n/a	Pittsburgh	n/a	15217	USA	Sam Allan
7	n/a	cmu	11/13/10	Tenant	n/a	n/a	n/a	IfcPersonAndOrg	n/a	n/a	n/a	Ann	Scott	Penn	n/a	Pittsburgh	n/a	15217	USA	Ann Scott
8	n/a	cmu	11/14/10	HVAC Engineer	zz	n/a	n/a	IfcPersonAndOrg	n/a	n/a	n/a	Bob	Parker	Penn	n/a	Pittsburgh	n/a	15217	USA	Bob Parker

Figure 4-21 *DirectwAggregation* –

'FirstName + LastName' from 'Contact' sheet, 'GivenName, FamilyName' columns

3. LEED Attribute

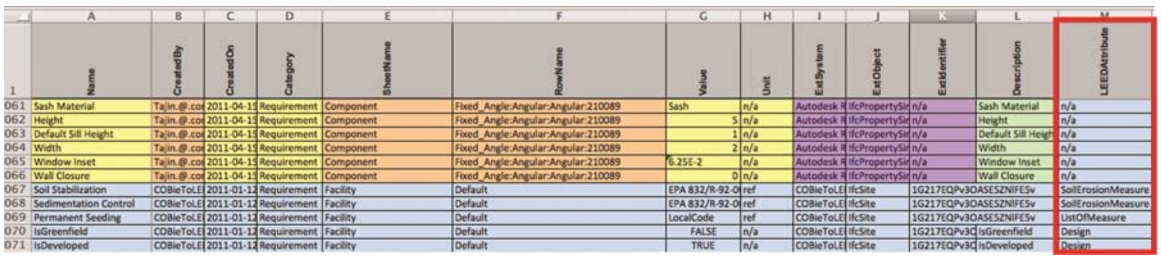
This type of data is related to a COBIE-augmented required LEED value and is referenced as *LEEDAttribute* — see Figure 4-22.



G	H	I	J	K	L	M	N	O
LEEDDat	LEED	LEEDDataT	COBieSheet	COBieColumn	COBieInformatic	TypeForIn	COBieImplementationCondition	COBieImplementationValue
Single	Null	Null	Contact	FamilyName+	DirectwAggregat	DirectwA	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.GivenName + Contact.Family
List	SSp1	SEM	Document	SoilErosionMe	LEEDattribute	Direct	Document.Category == SoilErosionMeasure	Document.Name
List	SSp1	SEM	Document	SoilErosionMe	LEEDattribute	Direct	Document.Category == SoilErosionMeasure	Document.Reference
Single	Null	Null	Contact	FamilyName+	DirectwAggregat	DirectwA	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.GivenName + Contact.Family
List	SSp1	LOM	Document	ListOfMeasure	LEEDattribute	DirectwA	Document.Category == ListOfMeasure	Document.Name
List	SSp1	LOM	Document	ListOfMeasure	LEEDattribute	DirectwA	Document.Category == ListOfMeasure	Document.Reference
Single	Null	Null	Null	Null	LEEDvariable	LEEDvaria	Null	Null
Single	Null	Null	Contact	FamilyName+	Direct	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.GivenName + Contact.Family
Single	Null	Null	Contact	Company	Direct	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.Company
Single	Null	Null	Contact	Category	Direct	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.Category
Single	Null	Null	Contact	Null	LEEDvariable	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.Signature
Single	Null	Null	Contact	CreatedOn	Direct	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.CreatedOn
Single	Null	Null	Document	FamilyName+	DirectwAggregat	Direct	(Contact.Category == Civil Engineer) || (Contact.Category == UserDefined)	Contact.GivenName + Contact.Family
Single	Null	Null	Attribute	Name	LEEDattribute	Direct	(Attribute.ExtObject == IfcSite) && (Attribute.Description == IsPrimeFarmla	True/False
Single	Null	Null	Attribute	Name	LEEDattribute	Direct	(Attribute.ExtObject == IfcSite) && (Attribute.Description == IsAboveFloodl	True/False
Single	Null	Null	Attribute	Name	LEEDattribute	Direct	(Attribute.ExtObject == IfcSite) && (Attribute.Description == IsHabitatland)	True/False

Figure 4-22 LEED Attribute data classification for computable LEED rules

These data types have to be added into the COBie sheets by adding additional column/s. Such data cannot be held in any other way. Some elements that already exist in COBie may require additional information. To facilitate this, one or more columns are added as shown in Figure 4-23, ‘ LEEDAttribute’ is added to hold such attributes as ‘isGreenfield’ for IfcSite, and information such as ‘design’ to enable querying. The factors considered in writing the rules followed the process of starting with the directly retrievable information for example the Sheet name and original columns such as ‘ExtObject’ and query standard elements such as IfcPerson, IfcSite, etc. If the desired element is not retrievable then additional conditions are added such as ‘Description’ or ‘RowName’. When that does not suffice then query is directed to the added column such as ‘LEEDAttribute’ to find the necessary information.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Name	CreatedBy	CreatedOn	Category	SheetName	RowName	Value	Unit	ExtSystem	ExtObject	ExtIdentifier	Description	LEEDAttribute
061	Sash Material	Tajin.@.co	2011-04-15	Requirement	Component	Fixed_Angle:Angular:Angular:210089	Sash	n/a	Autodesk R	IfcPropertySin	n/a	Sash Material	n/a
062	Height	Tajin.@.co	2011-04-15	Requirement	Component	Fixed_Angle:Angular:Angular:210089	5	n/a	Autodesk R	IfcPropertySin	n/a	Height	n/a
063	Default Sill Height	Tajin.@.co	2011-04-15	Requirement	Component	Fixed_Angle:Angular:Angular:210089	1	n/a	Autodesk R	IfcPropertySin	n/a	Default Sill Heigh	n/a
064	Width	Tajin.@.co	2011-04-15	Requirement	Component	Fixed_Angle:Angular:Angular:210089	2	n/a	Autodesk R	IfcPropertySin	n/a	Width	n/a
065	Window Inset	Tajin.@.co	2011-04-15	Requirement	Component	Fixed_Angle:Angular:Angular:210089	6.25E-2	n/a	Autodesk R	IfcPropertySin	n/a	Window Inset	n/a
066	Wall Closure	Tajin.@.co	2011-04-15	Requirement	Component	Fixed_Angle:Angular:Angular:210089	0	n/a	Autodesk R	IfcPropertySin	n/a	Wall Closure	n/a
067	Soil Stabilization	COBieToLE	2011-01-12	Requirement	Facility	Default	EPA 832/R-92-0	ref	COBieToLE	IfcSite	1G217EQPv3OASESZNIFESv		SoilErosionMeasure
068	Sedimentation Control	COBieToLE	2011-01-12	Requirement	Facility	Default	EPA 832/R-92-0	ref	COBieToLE	IfcSite	1G217EQPv3OASESZNIFESv		SoilErosionMeasure
069	Permanent Seeding	COBieToLE	2011-01-12	Requirement	Facility	Default	LocalCode	ref	COBieToLE	IfcSite	1G217EQPv3OASESZNIFESv		ListOfMeasure
070	IsGreenfield	COBieToLE	2011-01-12	Requirement	Facility	Default	FALSE	n/a	COBieToLE	IfcSite	1G217EQPv3C	IsGreenfield	Design
071	IsDeveloped	COBieToLE	2011-01-12	Requirement	Facility	Default	TRUE	n/a	COBieToLE	IfcSite	1G217EQPv3C	IsDeveloped	Design

Figure 4-23 LEED Attribute added column in Attribute sheet

4.2.4 Integrating Building information and Rules for Assessment

To support building information requirement for sustainable design pre-assessment, a demonstrator prototype was developed, using the aforementioned modules (LEED templates, COBie+ data structure and rating system rules) (see Figure 4-24 and Figure 4-25).

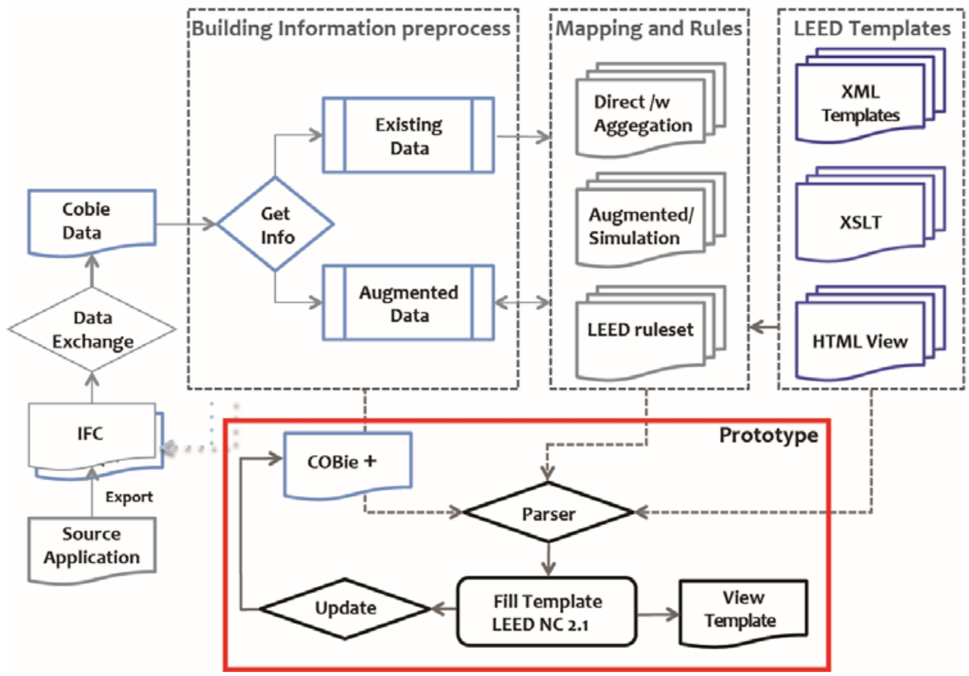


Figure 4-24 Prototype development for pre-assessment support

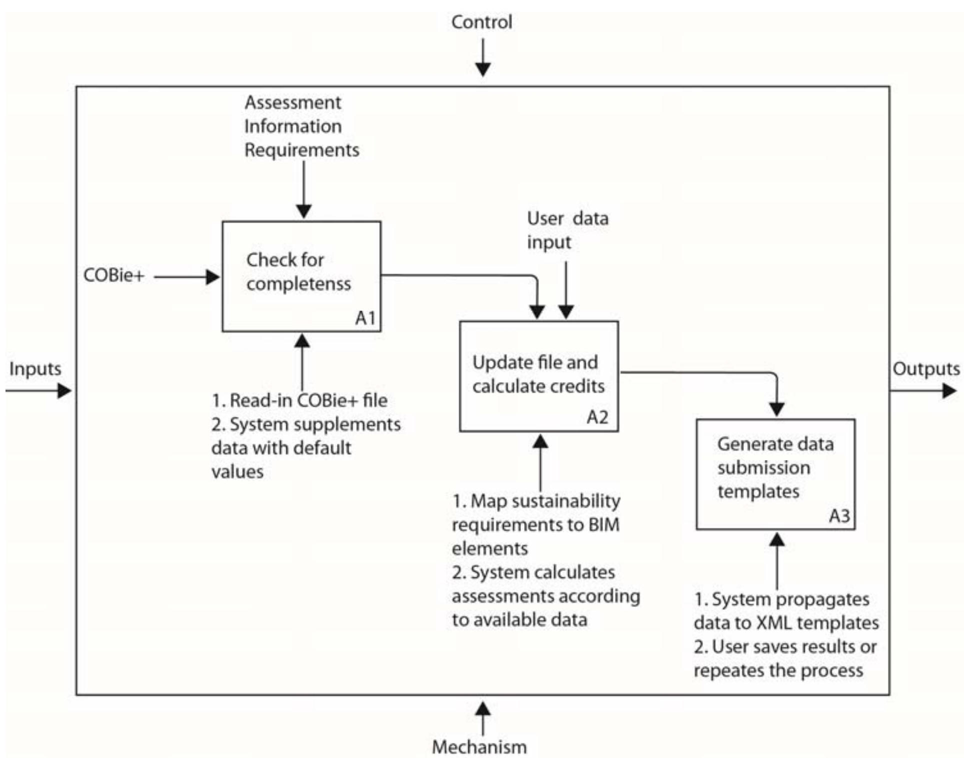


Figure 4-25 Functional requirements for prototype development

The modules, and integration of the modules were programmed in Java. [23] Before functional requirements of the prototype could be met, COBie data was pre-processed. During translation from IFC to COBie a number of issues were addressed, which were divided into two phases: 1) data requirements in the model; and 2) applying LEED requirement rules to query and fill the LEED assessment templates. The functional requirements are met in the second phase.

In phase one, data requirements are met in the following way. First, potential loss of information during information during translation is controlled through specific settings to the translation software (AEC (AEC 3, 2012). Second, the COBie+ structure is created to accommodate additional necessary information. This involves addition of columns according to

Table 4-3.

In phase two, the first functional requirement of the prototype reads in a COBie+ file. This file is checked for data completeness; it searches for basic elements that need to be present for pre-assessment. These elements are defined as a combination of representative IFC elements and formulated LEED requirements. Data added correspond either to attributes of existing elements, for example, IfcSite or IfcSanitaryTerminalType, or to information external to the building model, for example, occupant number, area of surrounding buildings, ground cover type and corresponding runoff values etc. For example, the following code sample shows checking for 'Civil Engineer' and 'IfcPersonAndOrganization' in the 'Contact' sheet. If this element is not found then a row is added to COBie with some default values (Figure 4-26). Figure 4-27 shows COBie Contact sheet before checking, after the check is run, it adds two rows with 'Contactor' and 'Owner' with placeholders with default value in them (Figure 4-28).

[23] The parser shown in (Figure 4-24) was developed by Tsung-Hsien Wang. The user interface for the prototype was jointly developed with Varvara Toulkeridou.

```java
// go through the rows and look for civil engineer if not found add to list
for (int j = 0; j < sheet.getRows(); j++) {
    if (sheet.getCell(idCategory, j).getContents()
            .equals("Civil Engineer")&& sheet.getCell(idCategory, j).getContents()
            .equals("IfcPersonAndOrganization")) {
        civilEngeerIds.add(j);
    }
}
System.out.printf("Civil Engineer Row ID:%s\n\n", CivilEngineerRowID);
//create new hashtable for new sheet
Hashtable<Integer, LinkedList<String>> newSheetRowIds = new Hashtable<Integer, Link
// add this to the last when you finish adding new rows
inputSheetsRowIds.put("Contact", newSheetRowIds);
LinkedList<String> newRowColIds;
if (rSheet != null) {
    try {
        // if not found then add to the row and keep count for more than
        // one
        if (civilEngeerIds.size() < 1) {
            CivilEngineerRowID = rSheet.getRows();
            newRowColIds = new LinkedList<String>();
            eWriter.addLabel(rSheet, idCategory, CivilEngineerRowID,
                    "Civil Engineer");
            newRowColIds.add("Civil Engineer");
            eWriter.addLabel(rSheet, idEmail, CivilEngineerRowID,
                    "default");
            newRowColIds.add("default");
            eWriter.addLabel(rSheet, idFamilyName, CivilEngineerRowID,
                    "default");
            newRowColIds.add("default");
            eWriter.addLabel(rSheet, idGivenName, CivilEngineerRowID,
                    "default");
            newRowColIds.add("default");
            eWriter.addLabel(rSheet, idExternalObject,
                    CivilEngineerRowID, "IfcPersonAndOrganization");
```

Figure 4-26 Checking and augmenting Contact sheet with required element

	A	C	D	E	F	G	H	I	J	K	L	M
1	Email	CreatedOn	Category	Company	Phone	ExternalSystem	ExternalObject	ExternalIdentifier	Department	OrganizationCode	GivenName	FamilyName
2	n/a	2010-11-10T1	structuralengineer	AEC3	n/a	ArchiCAD 12.0	IfcPersonAndOrganization	n/a	AEC3	AEC3	Kerstin	Hausknech
3	n/a	2010-11-10T1	n/a	Undefined	n/a	ArchiCAD 12.0	IfcPersonAndOrganization	n/a	Undefined	Undefined	n/a	Undefined
4	Harriett.Shupp @CivilEngin	2011-01-12T0	Civil Engineer	Engineerin	412 777 99	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Harriett	Shupp
5	Lonnie.Files@Architect.con	2011-01-12T0	Architect	Architects	n/a	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Lonnie	Files
6	Sam.Kurt@Tenant.com	2011-01-12T0	Tenant	Rent	n/a	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Sam	Kurt
7	Erik.Faivre@HVACEngineer	2011-01-12T0	HVAC Engineer	Engineerin	n/a	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Matt	Erik
8	Mary.Saundra@ProjectMar	2011-01-12T0	Project Manager	Managerial	n/a	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Mary	Saundra

Figure 4-27 Contact sheet before checking

	A		B	C	D	E	F	G	H	I	J	K	L	M
1	Email		CreatedBy	CreatedOn	Category	Company	Phone	ExternalSystem	ExternalObject	ExternalIdentifier	Department	OrganizationCode	GivenName	FamilyName
2	n/a	n/a	n/a	2010-11-10T1	structuralengineer	AEC3	n/a	ArchiCAD 12.0	IfcPersonAndOrganization	n/a	AEC3	AEC3	Kerstin	Hausknech
3	n/a	n/a	n/a	2010-11-10T1	n/a	Undefined	n/a	ArchiCAD 12.0	IfcPersonAndOrganization	n/a	Undefined	Undefined	n/a	Undefined
4	Harriett.Shupp @CivilEngin	CO	COBieToLE	2011-01-12T0	Civil Engineer	Engineerin	412 777 99	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Harriett	Shupp
5	Lonnie.Files@Architect.com	CO	COBieToLE	2011-01-12T0	Architect	Architects	n/a	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Lonnie	Files
6	Sam.Kurt@Tenant.com	CO	COBieToLE	2011-01-12T0	Tenant	Rent	n/a	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Sam	Kurt
7	Erik.Faivre@HVACEngineer	CO	COBieToLE	2011-01-12T0	HVAC Engineer	Engineerin	n/a	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Matt	Erik
8	Mary.Saundra@ProjectMar	CO	COBieToLE	2011-01-12T0	Project Manager	Managerial	n/a	COBieToLEED	IfcPersonAndOrganization	n/a	n/a	n/a	Mary	Saundra
9	default				Owner				IfcPersonAndOrganization				default	default
10	default				Contractor				IfcPersonAndOrganization				default	default

Figure 4-28 Contact sheet after checking

The second functional requirement is represented in the center box in Figure 4-25. It parses the COBie+ checked file with the LEED rule file provided. For each LEED Template field that needs to be filled there is a query to the COBie+ file. For example in the following Figure 4-29 and Figure 4-30 rules for LEED credit SSp1 (Sustainable Sites pre-requisite1: Erosion and Sedimentation Control) have to be assessed and filled. This particular example is shown as it was made the default template to show up first when the prototype opens. The first field in the template queried has the name of the Civil Engineer, which corresponds to XML ID LEEDSS-0001 in the mapping and rule file. The second and third fields are in a tabular format requiring the names of references for Soil Stabilization (XML ID LEEDSS-0002 and XML ID LEEDSS-0003). In the augmented COBie+ file these sort of information fall into the LEEDAttribute information type as discussed in Section 4.2.3. The queried file retrieves 'IfcDocument' with the unique name of the particular document. Depending on the number of documents related to this query the number of rows in the table will vary. In this case there is one row for the Soil Stabilization and one for Soil Sedimentation. Figure 4-29 shows the XML file with the rest of the IDs as they are filled from the COBie + file, namely from ID LEEDSS-0004 to ID LEEDSS-0012.

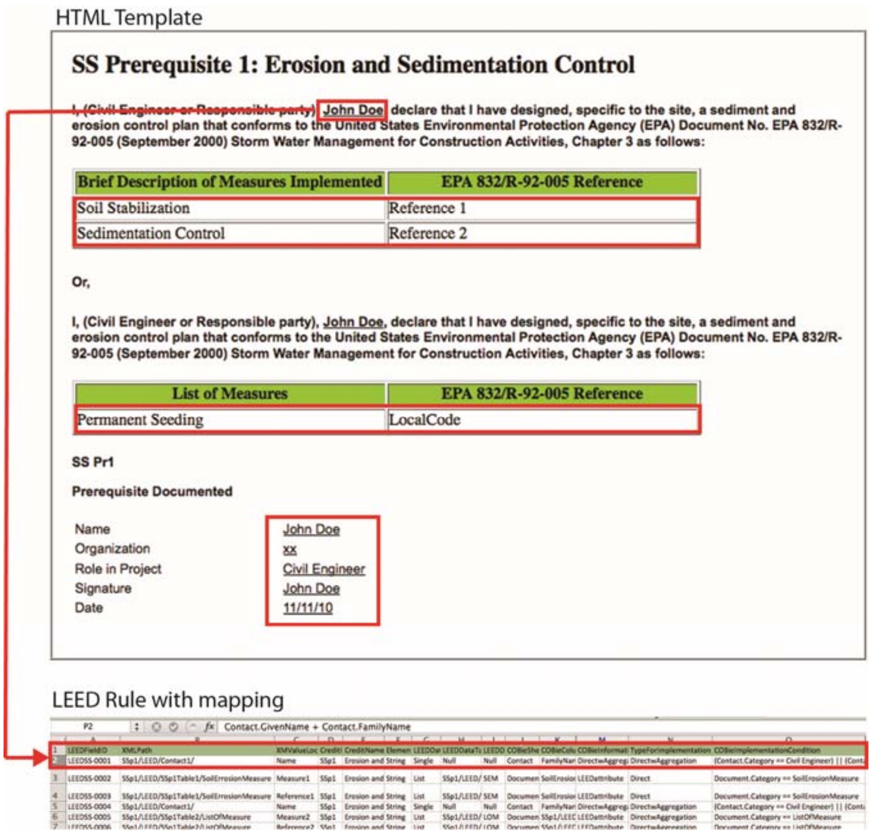


Figure 4-29 Querying COBie with computable LEED rules to assess and fill temples

Figure 4-30 LEED credit SSp1 XML filled from query

Once the query is done the results are propagated to the XML templates and converted to HTML format for viewing (Figure 4-31). A user interface is created to make these functions more easily accessible. In the user interface Sustainable Sites Prerequisite category is the default opening template. It is shown as an example in explaining the prototype.

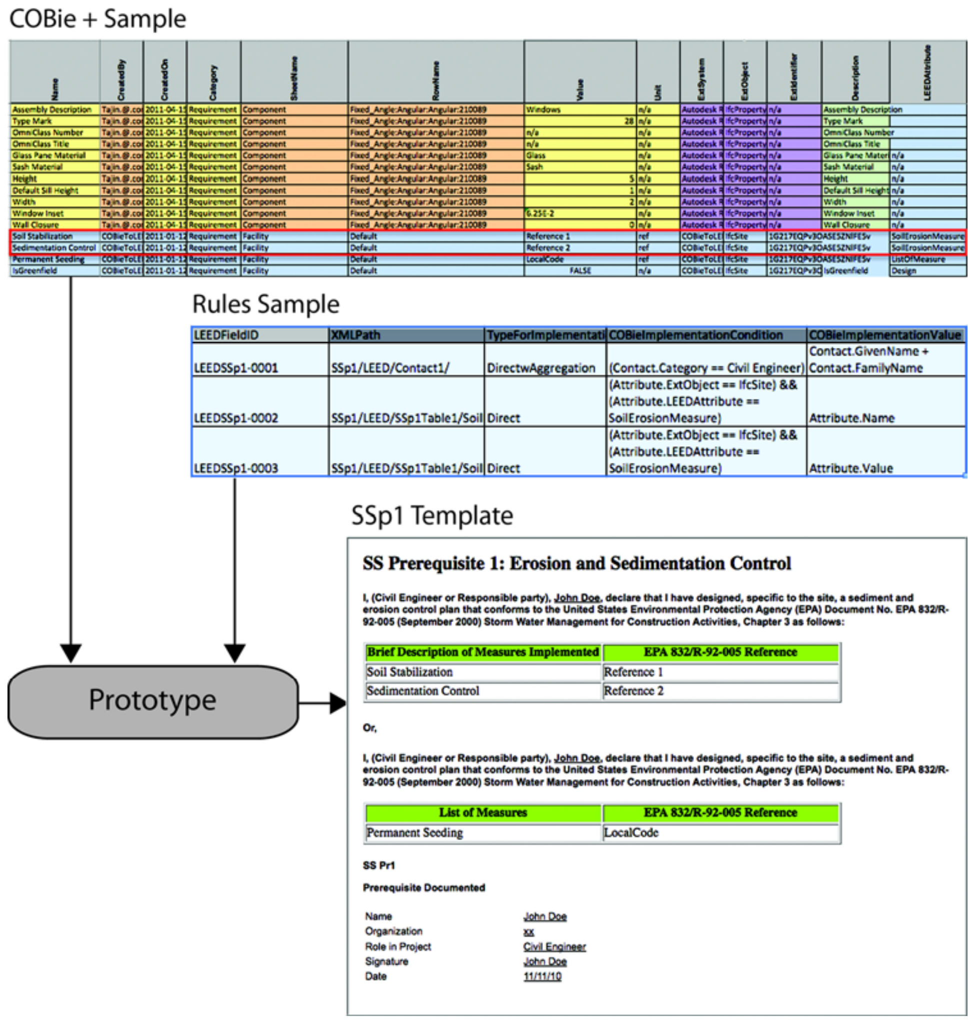


Figure 4-31 Prototype using COBie + and computable LEED rules to assess and fill temples

In the third functional requirement, a user interface is developed to view, and save the templates. After viewing the results in the template there is an option for the user to update and edit the COBie file. Figure 4-32 shows the prototype user interface (UI). On the top of the UI, is the file selection button, enabling user to select a' COBie file for assessment. Below that is a pull down menu to select the categories in LEED such as Sustainable Sites, Energy and Atmosphere, Materials and Resources, Water Efficiency, etc., to the right is the pull down menu for each template under the chosen category. The Sustainable Sites category is the default category when the process runs for the first time. The filled template is displayed in the center. At the bottom are three buttons; two of them are used to export the filled templates. The 'UserInput' button is used to edit the COBie file once the file is loaded and templates filled from the file.

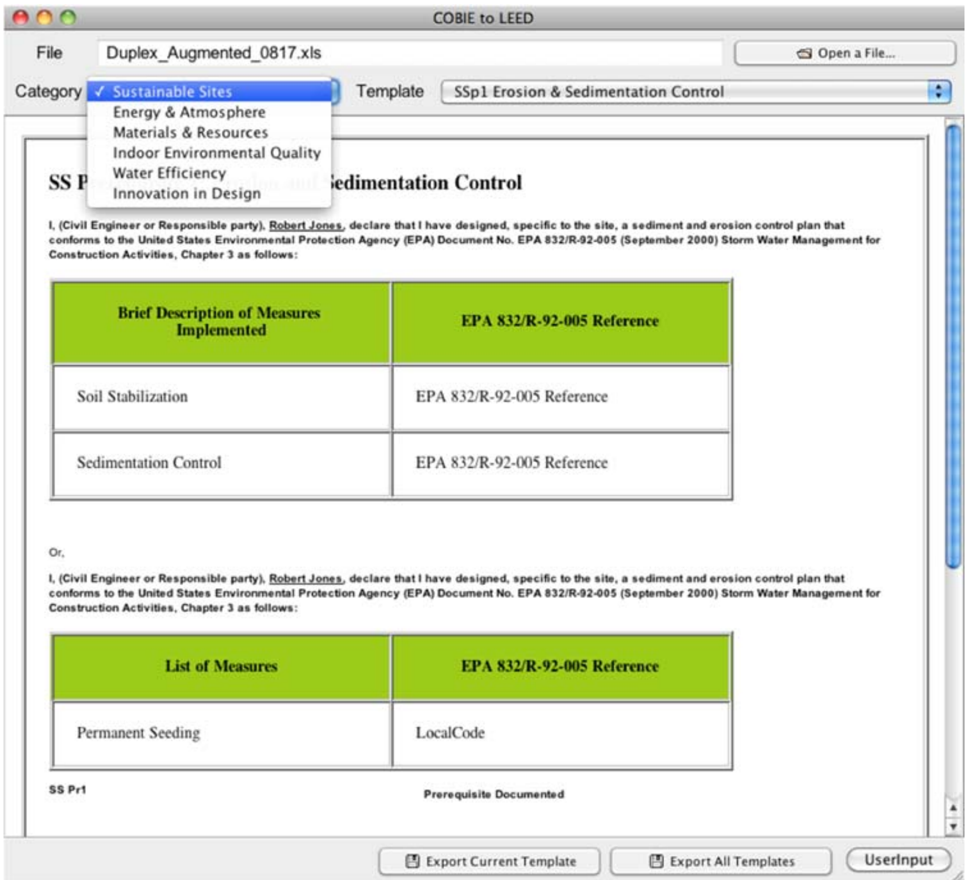


Figure 4-32 Prototype user interface

As illustrated in Figure 4-31, the rules for LEED credit SSp1 (Sustainable Sites pre-requisite1: Erosion and Sedimentation Control) requires that a 'Civil Engineer' is present in the project. This is a 'DirectwAggregation' data type as shown in Figure 4-21 and retrieved from the 'Contact' sheet. Data supporting 'soil erosion measure' is necessary in order to fill tables in the template. For implementation this particular value is treated as an attribute of' IfcSite'. Although 'IfcSite' is present in the original project information, this particular attribute is an augmented value. In this case study example, 'Soil Stabilization' represents 'soil erosion measure implemented', it is an augmented attribute of IfcSite with a default value of 'Reference1' shown in Figure 4-31.

The user can check, change and submit any information added to the model. Figure 4-33 illustrates user checking and insertion of missing information for the Category 'Civil Engineer,' which is required for assessing the Sustainable Sites SSp1 Erosion and Sedimentation Control credit. It should be noted that the default value of the Civil Engineer's name 'John Doe' has been changed to 'Robert James' and 'Reference1' has been updated to a specific name 'EPA 832/R-92-005 Reference'.

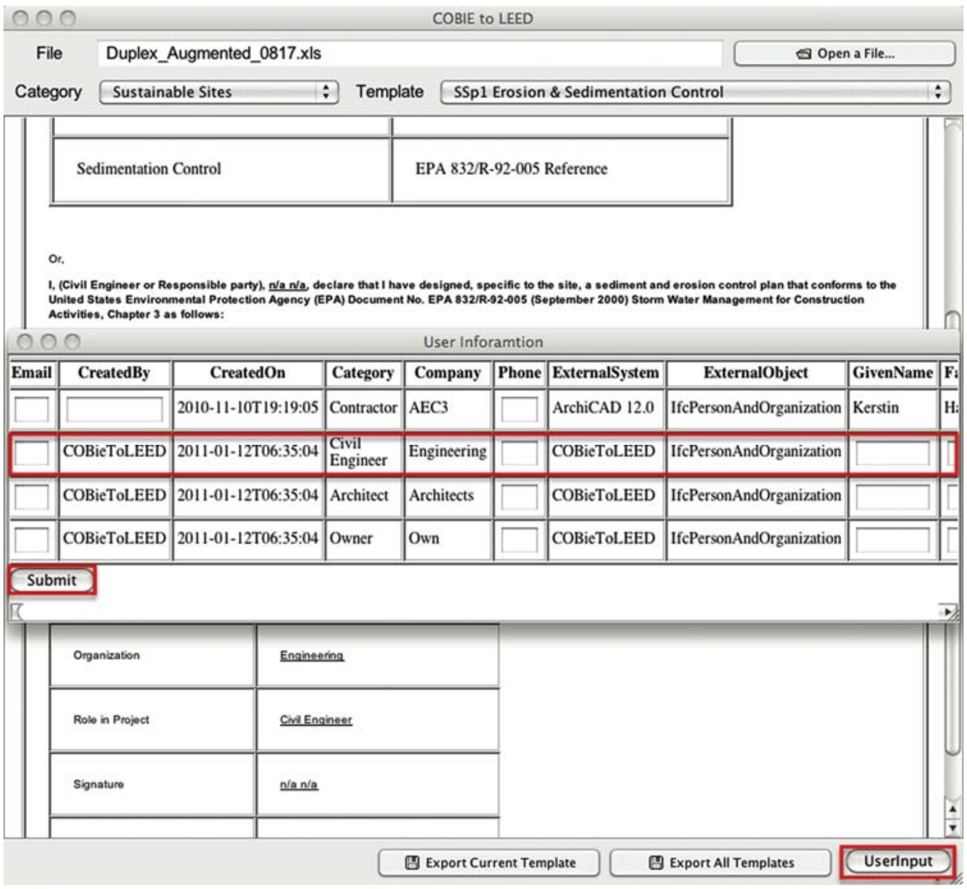


Figure 4-33 User checking and inserting missing information for filling SSp1

4.2.5 Assumptions and challenges

Certain assumptions were made in preparing the COBie sheets for evaluation. These are: (i) building data comes from a translated BIM; (ii) data required for LEED evaluation is augmented either by adding new data sets to the original COBie format or by augmenting the structure; and (iii) preprocessed data, typically requiring simulation, such as energy usage, or lighting qualities of a space, e.g., whether 75% of spaces are naturally lit, require the COBie structure to be augmented.

The challenges lay in identifying the kinds of information that would readily translate to COBie, and determining how and where to store the requisite information for LEED evaluation. From a data storage perspective the original data structure requires extension, without altering its basic premise and purpose. From a LEED perspective, both qualitative and quantitative measures need to be assessed through the LEED queries. Qualitative measures in LEED are categorized as those that require user input and are verified by the presence or absence of certain documents as required—these are stored in the 'Documents' spreadsheet. Quantitative measures are processed by queries to mapped entities in COBie. Quantitative values can be numeric, for example, building area or the volume of recycled material used; string, for example, as in the name of plumbing fixtures; or reference, for example, to names of objects. Data is extracted and collected from the given database by invoking the assessment rules codified in the mapping database. The mapping database maintains the underlying interoperation mechanisms for the various data structures.

4.3 Findings using case of two credits

The change of data usage and capability of the process and application are discussed with a sample LEED Water Efficiency (WE) credit and LEED Energy and Atmosphere (EA) credit over the three versions LEED 2.1, LEED 2009 and LEED v4.

4.3.1 Water Efficiency Credit Case 1

Using the mapping process and prototype application, templates and mapping files were created initially for LEED 2.1 WEc3 (Water Use Reduction), LEED 2009, WEp1 (Water Use Reduction 20%) and finally for LEED v4 WE102 (Prerequisite Indoor Water Use Reduction) to test the viability of the approach proposed. The data requirements and comparison for the overall category is shown in Table 4-7. By looking at the data for filling water use reduction across the three versions of LEED, minor increase is seen in LEED 2009 with 7% increase, and major increase is seen in LEED v4 with 143% increase (Table 4-8). In LEED 2009 the 7% increase is related mostly to new credit elements such as fixture ID and fixture group shown in Figure 4-36.

Table 4-7 Comparison of LEED 2.1, LEED 2009 and LEED v4 template data for Water Efficiency

Water Efficiency	Credit Description	LEED 2.1	LEED 2009	LEED V4
*WEp1	Prerequisite indoor water use reduction	na	82	116
WEp2	Prerequisite outdoor water use reduction	na	na	26
WEp3	Prerequisite water level metering	na	na	8
WEc1	Water Efficient Landscaping: Reduce by 50% or no potable water	21	44	Template sample not found
WEc2	Innovative Wastewater Technologies	30	na	na
WEc3	Water Use Reduction: 30% Reduction	*70	5	Template sample not found
WE110	Cooling Tower Water Use	na	na	17
WE112	Water Metering	na	na	10

* WEc3 in LEED 2.1 is equivalent to WEp1 in LEED 2009 and WE102 in LEED v4

Table 4-8 Increase in total data for LEED Water Efficiency over LEED versions 2.1, 2009, and v4

Credit Description	LEED 2.1	LEED 2009 total	LEED V4 total
Indoor water use reduction (WEc3, WEp1 and WE102)	70	14%	42%

The increased requirement in LEED v4 is attributed to specifying different indoor water fixture uses by type of users such as students, visitors, retail customers, and residential. Previously the users were divided by part time and full time and did not have to be categorized by user type, the total number of fixtures by type were enough. Out of the 116 minimum data points almost 100 need to be filled in a pre calculation spreadsheet and has to be submitted along with the template. The data points to be filled in the main template are thus reduced to 16 data points. These were mainly in the form of user input or new documents that have to be uploaded. Figure 4-34 shows breakdown of new credit element requirements across all WE credits over three versions of LEED. It maybe noted that the credit that is compared appears in different columns as they have been renamed in different versions despite measuring the general criteria- Indoor Water Use Reduction. In LEED v4, WEp3, WEc4 and WEc5 are new credits.

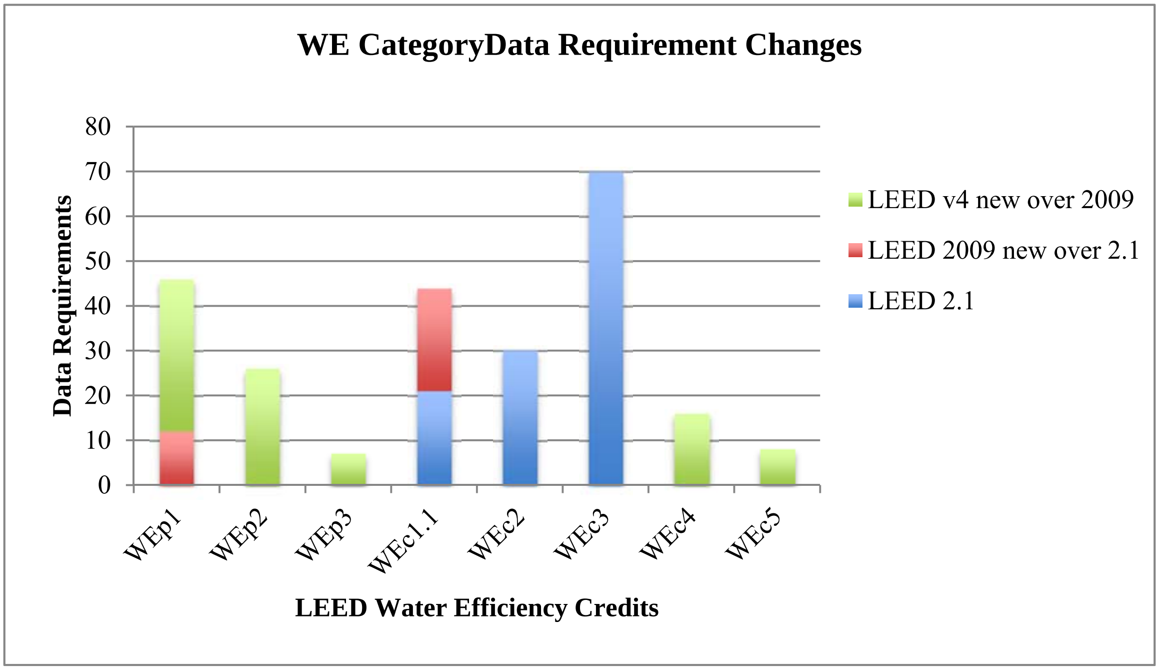


Figure 4-34 New requirements for Water Efficiency credits

The output of selected template sections follows in Figure 4-35, Figure 4-36 and Figure 4-37. In LEED 2.1, Baseline and Design case flush and flow fixture duration, fixture flow rate and number of uses for male and females were required to calculate indoor water use. In LEED 2009, in addition to the requirements in the previous version the fixture IDs and groups were required. This was not available from the COBie model, thus these fields remain unfilled in the generated template in Figure 4-36. Although in LEED v4 the template itself is not long (Figure 4-37), the data for all fixtures and their users need to be filled in a multi-sheet Excel workbook and submitted.

Currently, the prototype is able to fill data in the templates provided the extra data necessary for the templates have been supplied. In this case 100 more credit elements need to be added to the existing framework database. Since the prototype can only propagate results in a XML file format, the new module would have to be written to fill Excel templates. The COBie + structure is able to store the necessary information as new attributes.

WE Credit 3: Water Use Reduction

I, (Tenant, Project Manager, HVAC Engineer, Civil Engineer or Responsible party), John , declare that the project uses as least 20% less water than baseline fixture performance requirements of the Energy Policy Act of 1992

Flow Fixture Type	Water Use [gpm]	Duration[sec]
Conventional Lavatory	2.5	15
Low-Flow Lavatory	1.8	15
Kitchen Sink	2.5	15
Low-Flow Kitchen Sink	1.8	15
Shower	2.5	300
Low-Flow Shower	1.8	300
Janitor Sink	2.5	15

Flush Fixture Type	Water Use [gpf]
Conventional Water Closet	1.6
Low Flow Water Closet	1.1
Ultra Low-Flow Water Closet	0.8
Composting Toilet	0.0
Conventional Urinal	1.0
Waterless Urinal	0.0

Design Case Table

Flush Fixture Type	Daily Uses	Flow Rate [gpf]	Duration [flush]	Occupant users	Sewage Generation [gal]
Water Closet(Male)	0	1.1	1	150	0
Water Closet(Female)	0	1.1	1	150	495
Composting Toilet(Male)	0	0.0	1	150	0
Composting Toilet(Female)	0	0.0	1	150	0
Waterless Urinal(Male)	1	0.0	1	150	0
Waterless Urinal (Female)	0	0.0	1	150	0

Figure 4-35 LEED 2.1 WE 3: Water use reduction template sample

Flow Fixture Type	Daily Uses	Flow Rate [gpf]	Duration [flush]	Occupant users	Sewage Generation [gal]
Conventional Sink	3	2.5	12	300	450
Kitchen Sink	1	2.5	12	300	150
Shower	0.1	2.5	300	300	375

Total Daily Volume (gal)	1470
Annual Work Days	260
Annual Volume	382200
Graywater or Stormwater[gal]	
Total Annual Volume [gal]	382200

Baseline Case Table

Flush Fixture Type	Daily Uses	Flow Rate [gpf]	Duration [flush]	Occupant users	Sewage Generation [gal]
Water Closet(Male)	1	1.6	1	150	240
Water Closet(Female)	3	1.6	1	150	720
Urinal(Male)	2	1.0	1	150	300
Urinal(Female)	0	0.0	1	150	0

Flow Fixture Type	Daily Uses	Flow Rate [gpf]	Duration [flush]	Occupant users	Sewage Generation [gal]
Conventional Sink	3	2.5	12	300	450
Kitchen Sink	1	2.5	12	300	150
Shower	0.1	2.5	300	300	375

Total Daily Volume (gal)	2335
Annual Work Days	260
Annual Volume	607100

WE Cr3 (1 point):Water Use Reduction 37%

Points Documented

Name	John
Organization	YY Company
Role in Project	Civil Engineer
Signature	MySignature
Date	MMDDYY

Figure 4-35 (continued)

LEED 2009 for New Construction and Major Renovation

WE PREREQUISITE 1: WATER USE REDUCTION 20% REDUCTION

The Table. Daily Occupancy below is a linked submittal from PI Form 3: Occupant and Usage Data to be used for reference only. PI Form 3 must be completed before values will display in WE Prerequisite 1. These values should inform, but not necessarily parallel, the numbers entered in the Table. Fixture Groups Definition.

Table. Daily Occupancy

FTE	Average Transients(Student/ Visitor)	Average Retail Customers	Residents	Total

Fixture Groups Introduction: This table allows for project occupants to be organized in a way that best represents fixture usage patterns in the project. Occupants can be grouped together or separated into sub-groups at the option of the project team. The usage groups defined must be derived from daily occupancy data for the project building. Accordingly, all project occupants, as recorded in the Daily Occupancy tables from PI Form 3: Occupant and Usage Data must be represented in the Table. Fixture Groups Definition below. All residential occupants should be represented separately from non-residential occupants. Refer to the additional guidance document in the Credit Resources section.

Table. Fixture Groups Definition

Group Name	Annual Days of Operation	FTE	Transients (Student / Visitor)	Retail Customers	Residents	Female %	Male %
	200	150	150	0.0	0.0	37.500	62.500

Briefly describe the inputs in the Table. Fixture Groups Definition. Explain the methodology used to define each fixture group, as well as the derivation of data in each row. Additionally, provide a detailed explanation if the default gender ratio is not used.

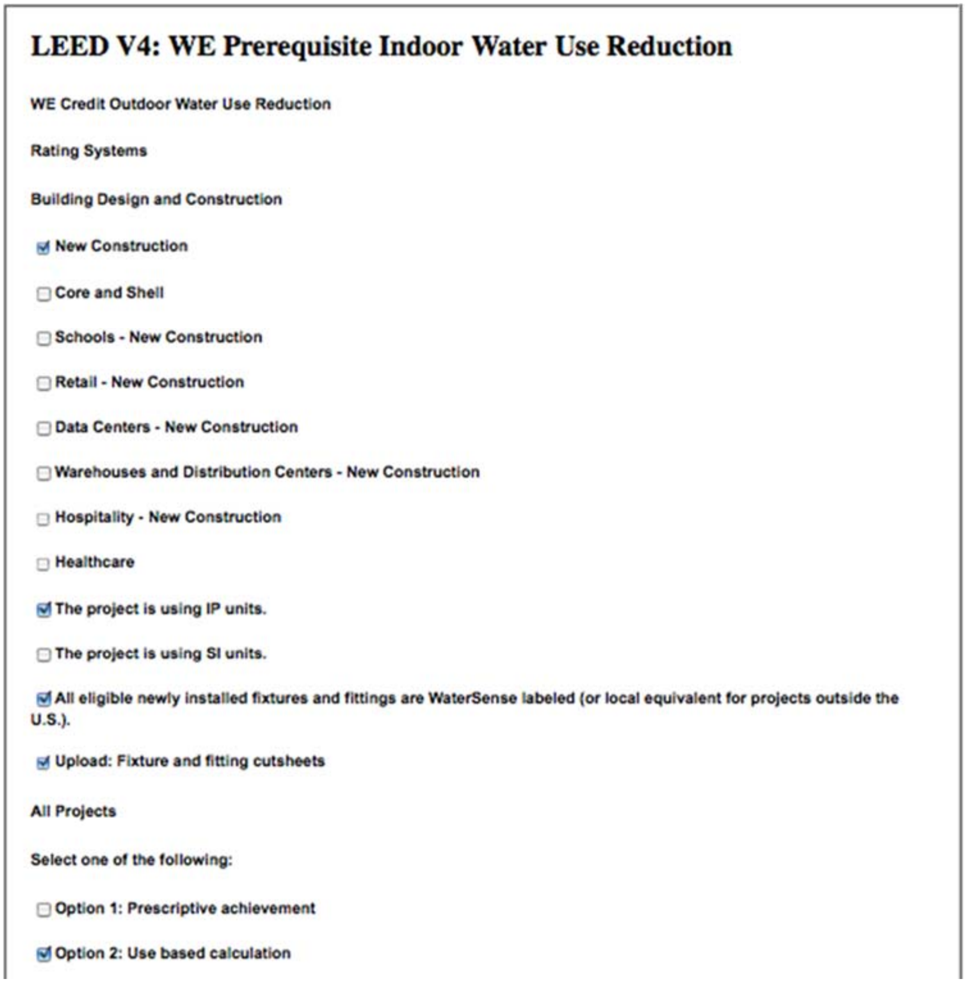
Table. Flush Fixture Data Baseline Case

Enter flush fixture data for each fixture group defined in the Table. Fixture Groups Definition

Select	Display	Fixture ID	Fixture Family	Fixture Type	Daily uses	Baseline	Installed	IPC Baseline	Performance
		n/a	Conventional Water Closet	FlushFixture	3	2.5	0.2	563	450
		n/a	Conventional Water Closet	FlushFixture	2	2.5	0.2	375	300
		n/a	Conventional Urinal	FlushFixture	2	1.6	1	960	0

Total calculated flush fixture water use volume, baseline case (kGal)	1890.00
Total calculated flush fixture water use annual volume, baseline case (kGal)	493480.00
Percent reduction of water use in flush fixtures (%)	60.0

Figure 4-36 LEED 2009 WEp1 template sample



LEED V4: WE Prerequisite Indoor Water Use Reduction

WE Credit Outdoor Water Use Reduction

Rating Systems

Building Design and Construction

☑ New Construction

☐ Core and Shell

☐ Schools - New Construction

☐ Retail - New Construction

☐ Data Centers - New Construction

☐ Warehouses and Distribution Centers - New Construction

☐ Hospitality - New Construction

☐ Healthcare

☑ The project is using IP units.

☐ The project is using SI units.

☑ All eligible newly installed fixtures and fittings are WaterSense labeled (or local equivalent for projects outside the U.S.).

☑ Upload: Fixture and fitting cutsheets

All Projects

Select one of the following:

☐ Option 1: Prescriptive achievement

☑ Option 2: Use based calculation

Figure 4-37 LEED V4 WE102 template sample

4.3.2 Energy And Atmosphere Credit Case 2

Of all of the categories, the Energy and Atmosphere category has evinced the greatest increase in the amount of required information. This is observed and tested for LEED 2.1 EAp2 (Minimum Energy Performance), LEED 2009 EAp2 (Minimum Energy Performance), and for LEED v4 EAp2 Minimum Energy Performance) credits for Option 1—Whole Building Simulation. Sections of the template outputs are given for the three versions. LEED 2.1 EAp2 requires a minimum of 8 fields to be entered (Figure 4-39) whereas LEED 2009 EAp2 requires a minimum of 420 data points. This represents a 319% increase for LEED 2009 from LEED 2.1 and 357% increase for LEED v4 from LEED 2.1. Table 4-9 shows a summary of all Energy and Atmosphere credit requirements. Figure 4-38 represents it in graphical form.

Table 4-9 Comparison of LEED 2.1, LEED 2009 and LEED v4 total data for Energy Efficiency

Energy And Atmosphere	**Credit Description**	**LEED 2.1**	**LEED 2009**	**LEED V4**
EAp1	Fundamental Commissioning of the Building Energy Systems	15	38	24
EAp2	Minimum Energy Performance	9	468	1207
EAp3	Fundamental Refrigerant Management	7	24	12
*EAp4	Energy Level metering	na	na	8
EAc1	Optimize Energy Performance	**10	**6	Template unavailable
EAc2	On-Site Renewable Energy	18	19	14
EAc3	Enhanced Commissioning	14	12	11
EAc4	Enhanced Refrigerant Management	7	27	22
EAc5	Measurement & Verification	25	13	Removed
EAc6	Green Power	11	22	19
*EA118	Advanced Energy Metering	na	na	9
*EA121	Demand Response	na	na	12

* New Credits in LEED v4 ** When simulation option is used

Table 4-10 New data for Minimum Energy Performance over LEED versions 2.1, 2009, and v4

Credit Description	**LEED 2.1 original**	**LEED 2009 new from 2.1**	**LEED V4 new from 2009**
EAp2: Minimum Energy Performance	9	5011%	73%

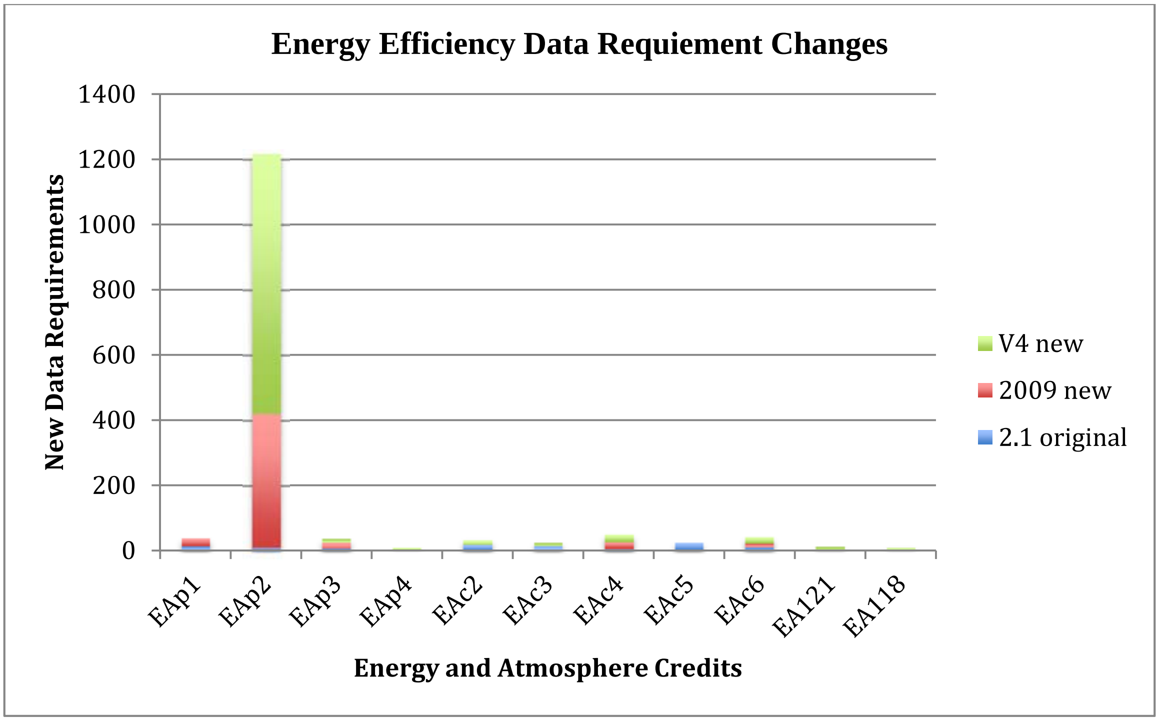
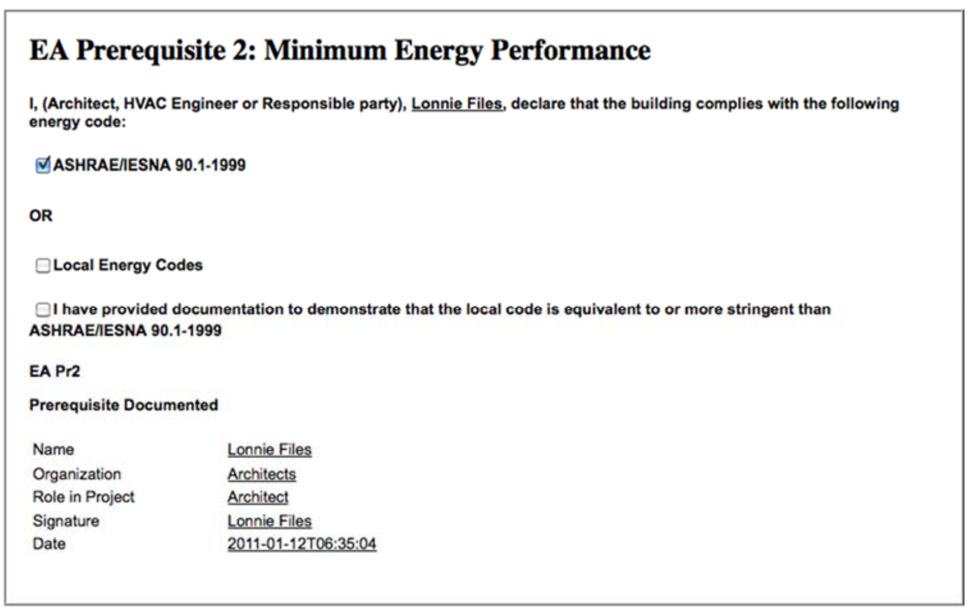


Figure 4-38 LEED Energy and Atmosphere category credit



EA Prerequisite 2: Minimum Energy Performance

I, (Architect, HVAC Engineer or Responsible party), Lonnie Files, declare that the building complies with the following energy code:

☑ **ASHRAE/IESNA 90.1-1999**

OR

☐ **Local Energy Codes**

☐ **I have provided documentation to demonstrate that the local code is equivalent to or more stringent than ASHRAE/IESNA 90.1-1999**

EA Pr2

Prerequisite Documented

Name	Lonnie Files
Organization	Architects
Role in Project	Architect
Signature	Lonnie Files
Date	2011-01-12T06:35:04

Figure 4-39 LEED 2.1 EAp2 template sample

LEED 2009 for New Construction and Major Renovation

EA PREREQUISITE 2: MINIMUM ENERGY PERFORMANCE

TARGET FINDER

The following fields are required, but the values have no bearing on EA Prerequisite 2 compliance. Use the Target Energy Performance Results calculator on the ENERGY STAR website to generate the values. If using prescriptive compliance paths (Options 2 or 3), leave the Design energy consumption and cost values blank in the Target Finder website, and set the Design values equal to the Target values in this form.

	Design	Target
Energy performance rating:		
CO2-eq emissions:		
CO2-eq emissions reduction:		

☐ **Upload EAp2-1. Provide the Target Finder Energy Performance Results for the project building (a screen capture or other documentation containing the same information).(Optional)**

☑ **The building is not able to get a Target Finder score because the tool does not support the primary building type of the project building. (Optional)**

PREREQUISITE COMPLIANCE

Project name: 407SCraig

Approximate project gross square footage/ meters:2915.05

Principal project building activity: Office

Select a compliance path:

☑ **Option 1: Whole Building Energy Simulation. The project team will document improvement in the proposed building performance rating as compared to the baseline building performance rating per ASHRAE/IESNA Standard 90.1-2007 or California Title 24-2005 Part 6.**

☐ **Option 2. Prescriptive Compliance Path: ASHRAE Advanced Energy Design Guide. The project team will document compliance with the ASHRAE Advanced Energy Design Guide.**

☐ **Option 3. Prescriptive Compliance Path: Advanced Buildings Core Performance Guide. The project team will document compliance with the Advanced BuildingsTM Core PerformanceTM Guide.**

OPTION 1. WHOLE BUILDING ENERGY SIMULATION

Figure 4-40 LEED 2009 EAp2 template sample sections

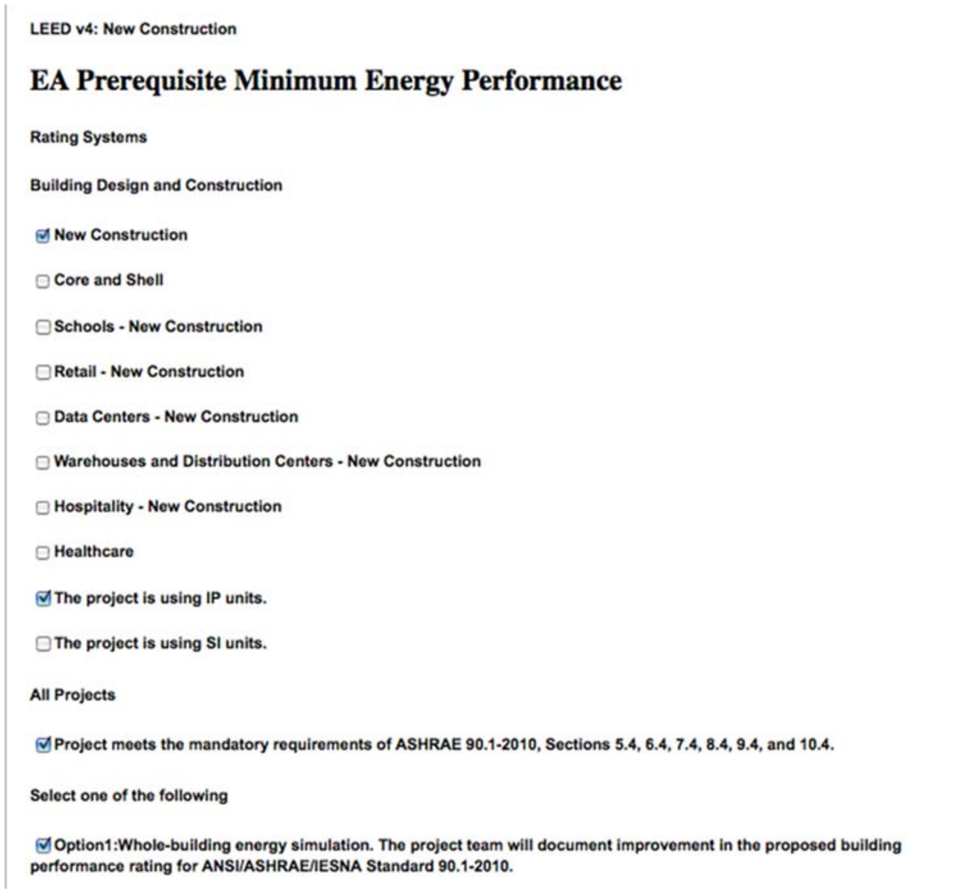
Table EAp2-4. Baseline Performance - Performance Rating Method Compliance

End Use	Process	Energy Type	AnnualDemand	AnnualValue	Baseline 0	Baseline 90	Baseline 180	Baseline 270	Baseline Results
Interior Lighting	☐	Electricity	Energy Use	KWh	879	879	879	879	879.000
Interior Lighting	☐	Natural Gas	Energy Use	KWh	0	0	0	0	.000
Interior Lighting	☐	Electricity	Energy Demand	W	1084	1084	1084	1084	1084.000
Interior Lighting	☐	Natural Gas	Energy Demand	W	0	0	0	0	.000
Exterior Lighting	☑	Electricity	Energy Use	KWh	1084	1084	1084	1084	1084.000
Exterior Lighting	☐	NaturalGas	Energy Use	KWh	0	0	0	0	.000
Exterior Lighting	☑	Electricity	Energy Demand	W	2490	2490	2490		.000
Exterior Lighting	☐	NaturalGas	Energy Demand	W	0	0	0	0	.000
Space Heating	☐	Electricity	Energy Use	KWh	28772	28889	28804	28530	28748.750
Space Heating	☐	NaturalGas	Energy Use	KWh	0	0	0	0	.000
Space Heating	☐	Electricity	Energy Demand	W	32405	32698	32054	32449	32401.500
Space Heating	☐	NaturalGas	Energy Demand	W	0	0	0	0	.000
Space Cooling	☐	Electricity	Energy Use	KWh	7032	7266	7178	7244	7180.000
Space Cooling	☐	NaturalGas	Energy Use	KWh	0	0	0	0	.000
Space Cooling	☐	Electricity	Energy Demand	W	13360	13800	13624	14239	13755.750
Space Cooling	☐	NaturalGas	Energy Demand	W	0	0	0	0	.000
Pumps	☐	Electricity	Energy Use	KWh	0	0	0	0	.000
Pumps	☐	NaturalGas	Energy Use	KWh	0	0	0	0	.000
Pumps	☐	Electricity	Energy Demand	W	0	0	0	0	.000
Pumps	☐	NaturalGas	Energy Demand	W	0	0	0	0	.000
Heat Rejections	☑	Electricity	Energy Use	KWh	0	0	0	0	.000
Heat Rejections	☑	NaturalGas	Energy Use	KWh	0	0	0	0	.000
Heat Rejections	☑	Electricity	Energy Demand	W	0	0	0	0	.000
Heat Rejections	☑	NaturalGas	Energy Demand	W	0	0	0	0	.000
Fans Interior	☐	Electricity	Energy Use	KWh	2197	2197	2197	2197	2197.000
Fans Interior	☐	NaturalGas	Energy Use	KWh	0	0	0	0	.000
Fans Interior	☐	Electricity	Energy Demand	W	1377	1377	1377	1377	1377.000
Fans Interior	☐	NaturalGas	Energy Demand	W	0	0	0	0	.000
Fans Parking	☐	Electricity	Energy Use	KWh	1377	1377	1377	1377	1377.000
Fans Parking	☐	NaturalGas	Energy Use	KWh	0	0	0	0	.000
Fans Parking	☐	Electricity	Energy Demand	W	6592	6592	6592	6592	6592.000
Fans Parking	☐	NaturalGas	Energy Demand	W	0	0	0	0	.000
Service Water Heating	☐	Electricity	Energy Use	KWh	0	0	0	0	.000
Service Water Heating	☐	NaturalGas	Energy Use	KWh	6299	6299	6299	6299	6299.000

Figure 4-40 (continued)

In Figure 4-40, sections of LEED 2009 EAp2 Minimum Energy Performance templates are shown. This template requires data from simulation to be explicitly shown. It involves type of energy code for example ASHRAE 90.1-2010, name of weather file, climate zone; name, area and occupancy of each space used in building, energy usage (lighting, heating and cooling, pumps, fans etc.) All the information is required for four baseline building energy performances and the design case. This huge amount of data and related credit elements required for energy performance is currently stored in the COBie sheet named 'System' for LEED 2009.

In LEED v4 all of the original information required for LEED 2009 has to be uploaded to a 'Minimum Energy Performance Calculator' spreadsheet, in addition there is substantially more information required for filling the spreadsheet. This option is seen in Figure 4-41.


LEED v4: New Construction

EA Prerequisite Minimum Energy Performance

Rating Systems

Building Design and Construction

- [x] New Construction
- [ ] Core and Shell
- [ ] Schools - New Construction
- [ ] Retail - New Construction
- [ ] Data Centers - New Construction
- [ ] Warehouses and Distribution Centers - New Construction
- [ ] Hospitality - New Construction
- [ ] Healthcare
- [x] The project is using IP units.
- [ ] The project is using SI units.

All Projects

- [x] Project meets the mandatory requirements of ASHRAE 90.1-2010, Sections 5.4, 6.4, 7.4, 8.4, 9.4, and 10.4.

Select one of the following

- [x] Option1:Whole-building energy simulation. The project team will document improvement in the proposed building performance rating for ANSI/ASHRAE/IESNA Standard 90.1-2010.

Figure 4-41 LEED v4 EAp2 template sample

In the current version of the prototype, data can only be propagated to XML templates, a new module would be needed to fill Excel templates.

4.4 Summary

This chapter presents an approach to sharing BIM information through a series of interoperation between two standard data structures, IFC and COBie. Data exchange for sustainability assessment is managed by a functional database approach. A prototype application to automate generation of LEED NC 2.1 templates within an integrative process is described. The potential contribution of this tool is an effective approach to storing, sharing and managing data between various building professions for the purpose of sustainable building assessment. The prototype uses a flexible approach, which will allow for easy update of assessment rules as rating systems evolve and change.

During the course of researching and developing this project, data required to fill LEED NC 2.1 templates were analyzed. Approximately, on average, 40% of the data is retrieved from the COBie model without augmentation; the remaining 60% is retrieved from data added to COBie. Out of this added data 40% can be identified as attributes of the building elements and includes data that has to be post processed from simulation results. The remaining 20% mainly pertain to queries for support documents that are required for submission.

This approach described has been tested to populate selected LEED NC 2009 templates. All templates have been created and the mapping between data requirements and existing database indicates a general increase in the amount of data required to assess credits. Table 4-11 summarizes the total data requirement change from LEED 2.1, LEED 2009 and LEED v4. The data points are counted for unique entries required for filling a template. In the Sustainable Sites (SS) category in LEED 2009 there is 46% increase of data requirements from LEED2.1, and for LEEDv4 there is 43% increase data requirement from LEED 2.1 or 9% reduction from LEED 2009. For the water Efficiency (WE) category the increase in total (minimum) data requirement in LEED 2009 is 39%, and 87% in LEED v4. The most significant amount of increase is seen in the Energy and Atmosphere (EA) category where there is 326% increase in LEED 2009 and 891% increase in LEED v4 from LEED 2.1. It may be noted that the major jump in data requirements came from filling simulation results for Prerequisite EAp2 (Minimum energy performance) option 1, in the template. In LEED v4 most of this data relates to more detailed information regarding the Heating, Ventilation and Air Cooling (HVAC) systems and components. In the Material and Resources category there is a 21% increase in LEED 2009 from LEED 2.1, in LEED v4 there is a decrease of 17%, this can be attributed to the fact that requirements are accumulated into documents rather than entering individual values and thus the reduction. The Indoor Environmental Quality (EQ) category is not shown for LEED v4, as there were a large number of templates that were unavailable online to compare data changes in LEED v4. Figure 4-42 shows a summary of the comparison of total information requirement change.

Table 4-11 Comparison of LEED 2.1, LEED 2009, and LEED v4 template total data requirements

LEED Categories	LEED 2.1	LEED 2009	LEED v4	Change 2009 from 2.1 (%)	Change v4 from 2.1 (%)	Change v4 from v4 (%)
SS	128	207	188	62	46%	-9
WE	92	128	162	39	87%	27
EA	135	575	1338	326	891%	133
MR	163	198	135	21	-17%	-32
EQ	163	369	-	126		-

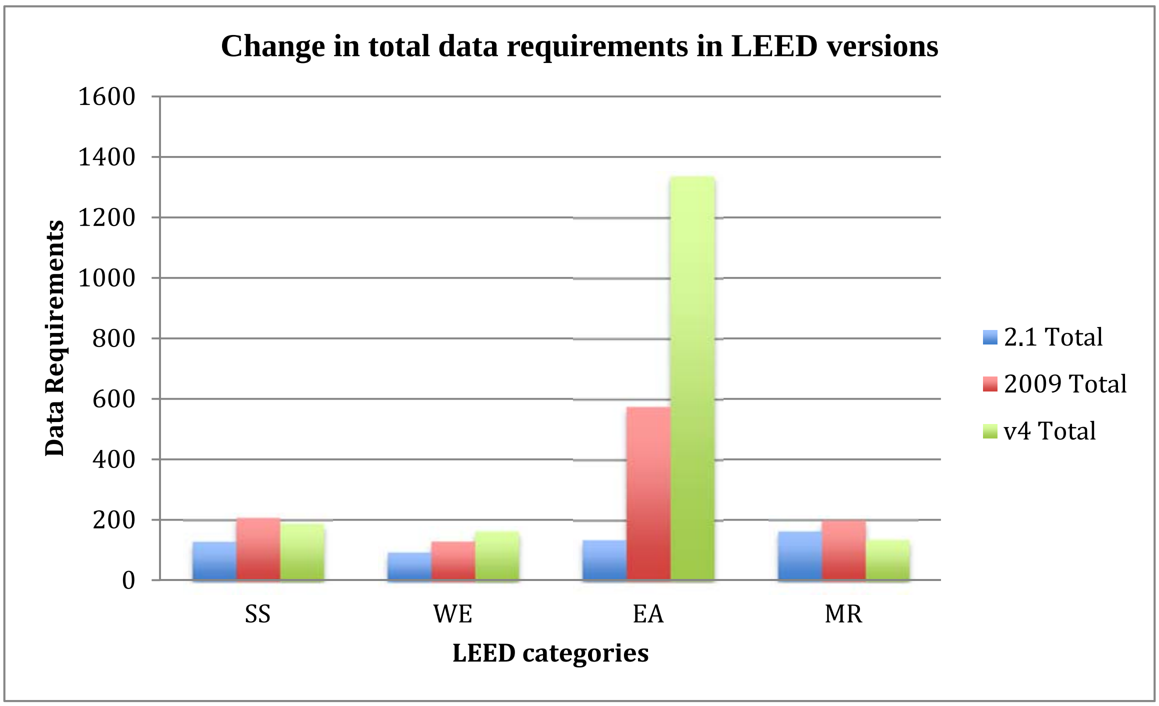


Figure 4-42 Change in total requirements over LEED versions

The requirement is analyzed for new requirements over previous versions, with LEED 2.1 showing the original; this is shown in Figure 4-43. At this point it the research issues that have surfaced asks an inherent question - how do we generalize the changing and increasing amount of information. An option for formalizing the informational needs is explored through the use of ontology in Chapter 5.

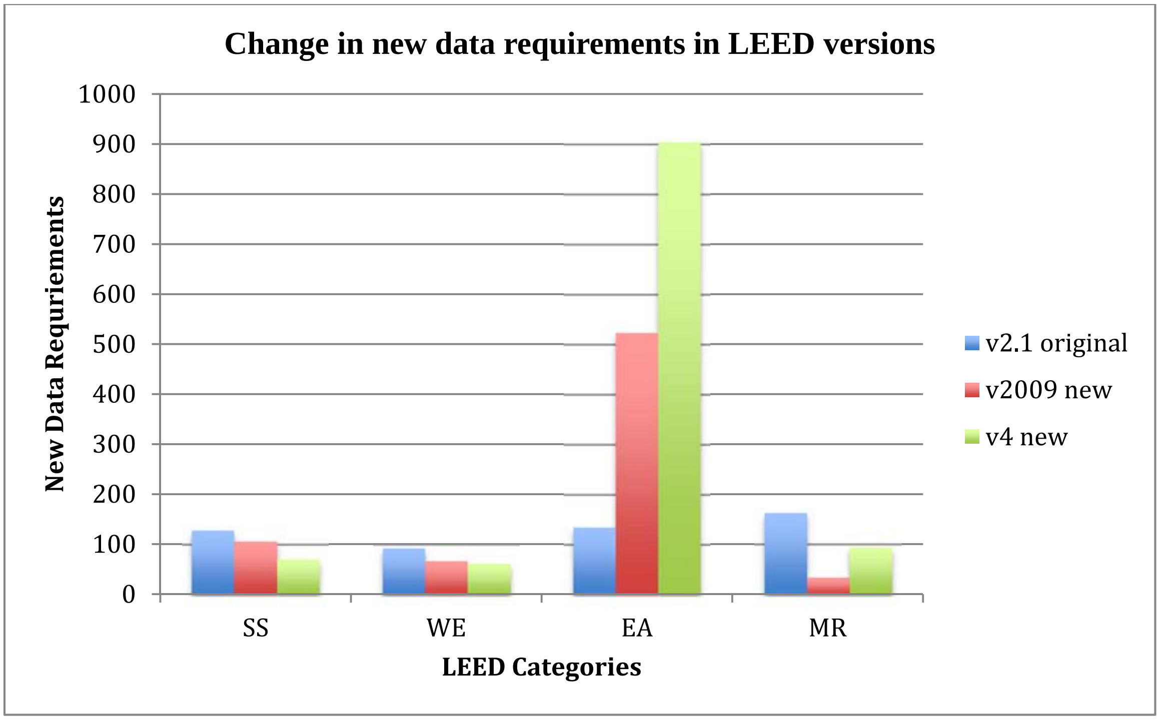


Figure 4-43 Change in new requirements from LEED 2.1

There are limitations to the work presented here. These are mainly due to information loss arising from the translation from BIM to COBie, and its unidirectional flow. The augmented COBie data structure and any added data cannot be fed back to the initial BIM due to the internal COBie to IFC mapping structure. Work on identifying, formalizing and mapping of required LEED data to possible IFC entities or 'Psets' will continue as long as rating systems evolve.

Chapter 5

Information formalization

In this chapter, a prototypical (partial) ontology is developed to represent entities in rating systems, design phases, elements from building information model i.e. represented in IFC and, and describes their relations. It is evident from Chapter 3 that existing IFC entities and their properties are not sufficient to support informational requirements from a rating system such as LEED. With new versions of the rating system the amount of information required from a building information model is increasing (Section 4.3). The intention is to improve the access of information initially required for creating a building model that contains information pertaining to a chosen sustainability rating system in a formalized way.

"Ontologies provide a framework for representing, sharing, and managing domain knowledge through a system of concept hierarchies (taxonomies), associative relations, and axioms that allows reasoning in a semantic way."
(El-Diarby, Lima, & Fies, 2005)

Such ontology is conceived to provide, in future research, a knowledge base that provides a flexible process to identify building elements and their relationships in assisting sustainability assessment. This approach is expected to improve the accessibility of information from an information design perspective and can be utilized for collaboration within a digital design environment. The information used to build the partial ontology is derived from the informational requirements formulated in Chapter 3.

5.1 Ontology Development for Formalization

To create an ontology for sustainable design assessment and information management, an ontology language is used to explicitly formalize and conceptualize the domain knowledge. The most common ontology languages include Resource Description Framework (RDF) and RDF Schema (RDFS), DAML +OIL (DARPA Agent Mark up Language and Web Ontology Language (OWL) (W3C (b), 2013). RDF provides data model specifications and XML (Extensible Markup language) syntax for modeling. RDFS offers specifications of class and property hierarchies for RDF. OWL is an extension of RDFS with additional vocabulary and formal semantics (W3C (b), 2013). In this research OWL is used to formulate the concepts and relationships required for sustainable building assessment. A free open source ontology editor Protégé (Protege, 2014) is used to compose the ontology that consist of three main blocks 1) class, 2) slots or properties and 3) facets or role restrictions. The scope of the partial sustainability ontology is limited to represent concepts, and relations used in determining rating system requirements in early design phases before it is tested for meeting sustainability standards. It focuses on the representation of the information required from a building information model as represented by IFC entities. The concept of cost/benefit generated during is excluded at this stage.

5.1.1 Representation of Concepts

Typically, the development of taxonomies includes varying degrees of judgment calls regarding classification requiring iterative development and input from domain experts. (El-Diarby, Lima, & Fies, 2005)The taxonomy for a sustainable information framework is a vocabulary that classifies and arranges sustainable rating requirement concepts in a hierarchical structure was developed through an iterative process with feedback from Autodesk's team. First, a glossary specific to sustainability assessment standards was developed. Second, restrictions were set to establish relationships between items in the glossary.

For each terminology the relationships between the concepts are formally defined. Although sustainable design and assessment requires a wide range of concepts, this research focuses on creating a partial model for assessing LEED NC v2.1 Water Efficiency credits. The main domain concepts are given in Table 5-1.

Table 5-1 Domain concepts of sustainability ontology

Domain Concept	Definition
Sustainability	Sustainability Categories and Rating system measures as defined by credit requirement
Model	Representation of required products provided by COBie or IFC
Phase	Measures of rating systems in building phases

Sustainability Concept

The knowledge entities in the taxonomy are derived from reviewing several rating systems such as LEED (USGBC, 2014), BREEAM (BREEAM (b), 2014), Green Star (GBCA (a), 2014) etc. for identifying their measures and requirements for evaluation. LEED has six main categories; Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Air Quality and Regional Priority and Innovations in Design, each addressing specific environmental concerns (USGBC, 2014). Similarly BREEAM has categories in Management, Energy, Pollution, Land use, Transport, Water, Health and Wellbeing, Materials, and Ecology. The sustainability category encompasses the broad criteria that are evaluated in different sustainable design rating standards such as water efficiency, ecology, culture, material, energy, indoor environment, site, transport, emissions, innovation etc. The rating concept includes rating systems such as LEED, BREEAM, Green Globes and Green Star. In this phase the main focus is in identifying and representing LEED2 and LEED3 requirements for assessment, in particular water efficiency credit criteria.

Model Concept

The entities source for developing 'Model' consists of the data structure in COBie, which contains Contact, Facility, Space, Type, Attribute, and Document at this stage. The IFC elements that are referenced to create COBie data are included in IFC class. Figure 5-1 shows the Sustainability concept (left) and Model and Phase concept (right), as they are being developed to support sustainability requirements.

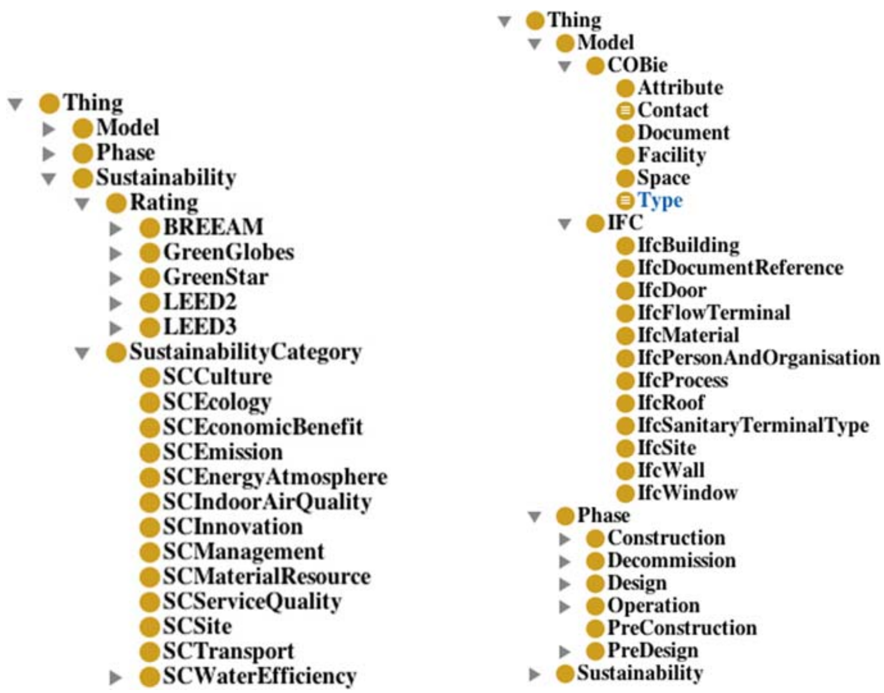


Figure 5-1 Taxonomy for Sustainability (left), Model and Phase (right) concepts

Phase Concept

The third concept consists of the metadata structure required for fulfilling sustainability assessment requirement. In order to create the entities for this concept, the lifecycle approach as classified by Geilingh (Geilingh, 1998) is used (Section 3.1.1). This concept essentially contains the entities required by rating systems for assessments; these elements may or may not be found in the COBie or IFC structure and thus will demonstrate where the information representation gaps are.

5.1.2 Relationship between Concepts

Relationship between the main sustainability concepts are defined by commonly accepted and intended relations, for example, 'inheritance', and 'collection'. *Inheritance* represents the relationship between a concept and its sub concepts, for example, LEED2WE (water efficiency) is a sub concept of LEED2 (refers to LEED 2.1). *Collection,* represents the relationship between concepts such that it constitutes relationship of 'has Requirement', 'has Representation' the concepts. Moreover relationships may have corresponding inverse relationships. If A is related to individual B in a certain relationship then its inverse property will link individual B to individual A. For example EfficientIrrigation 'has Representation' IfcFlowTerminal' and IfcFlowTerminal 'is representation of' EfficientIrrigation. In order to fulfill the credit requirements for Water

Efficiency credit 1 (LEED2_WE1), there is a minimum of 7 data points that need to be filled for assessment. For LEED2_WE3, there are 41

With the concept and relationships created, they are used to describe and define the classes. ‘Existential’ and ‘Universal’ restrictions can be set in protégé to define the relationship between classes. The Protégé manual defines the meaning of existential and universal restrictions as “Existential restrictions describe classes of individuals that participate in at least one relationship along a specified property to individuals that are members of a specified class.” (Horridge, 2011), The keyword ‘some’ is used to denote existential restrictions. Universal restrictions describe classes of individuals that for a given property only have relationships along this property to individuals that are members of a specified class. In Protégé 4.1, the keyword ‘only’ is used. For example existential relationship is created as LEED2WE_0001 ‘has some’ Person (Figure 5-2).

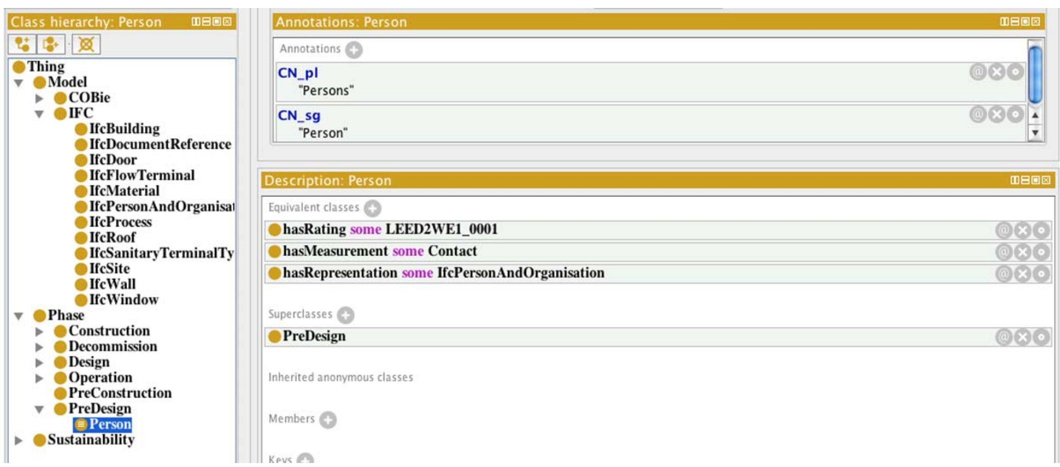


Figure 5-2 Protégé view of Person with restrictions applied

The ‘Person’ class ‘is used by’ LEED2WE_0001 to assess if any individual is present. Figure 5-3, Person is a class within the Phase concept that is related to LEED2WE1_0001 by having ‘hasRequirement’ relationship. Through the other established relationships Person can be seen with its COBie element Contact and IFC element IfcPersonAndOrganization.

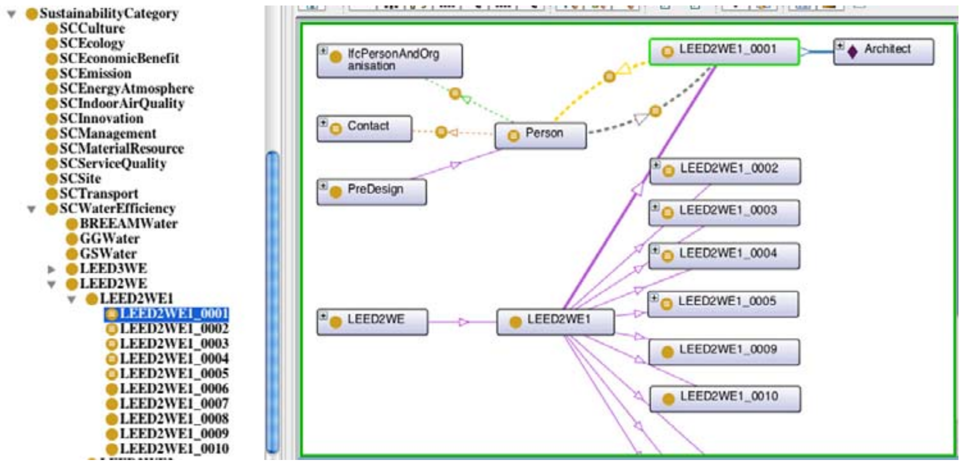


Figure 5-3 Protégé graph view shows the query of LEED2WE1_0001

The next section shows how information can be integrated with the knowledge concepts and retrieved consistently through an example.

5.2 Integration of Data

In ontology, instances in classes are optional, however, it is possible to import data by mapping the ontology to a data structure for assessment. For this demonstration TopBraid Composer (TopQuadrant, 2014) (Horridge, 2011) was used for a quick import of a building information model stored in COBie format by mapping the created ontology with COBie data source. This format was used as COBie provides a lightweight BIM that is available in SpreadsheetML.

To test the concepts and relationships of the ontology, some queries were created to see if they produced the desired element required for assessment. There are specific design goals that have to be met for any particular LEED certification, namely, silver, gold or platinum. Each goal is worth one point; the final certification is based on evaluation of the goals documented. In the ontology the goals of each credit are modeled to relate to the elements required for assessment, for example, Figure 5-4 shows LEED water efficiency credit LEED2WE1 with the subclasses that represent each field that needs to be filled in the assessment template. In this case LEED2WE1_0001 shows that the individual ‘Architect’ is available from the COBie data source. Similarly each of the other requirements can be queried.

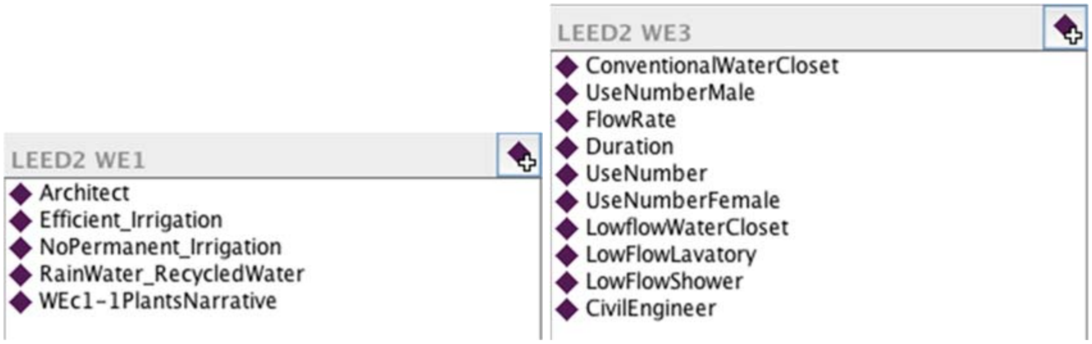


Figure 5-4 Simple Query shows list of individuals LEED2WE1 (left), and LEED2WE3 (right) credits from ontology

5.3 Summary

The ontology-driven approach for modeling sustainable building ratings has been proposed to support the formalization of information requirement for assessment from building designs. The current ontology is limited to partial model with limited entries. Ongoing research is dedicated to extending and refining classes, and relationships in the ontology to support sustainability requirements from rating systems perspective. It is expected that this will assist in organizing information requirement for sustainable building rating assessment and show the relationship between building elements and rating requirements for building evaluation.

Chapter 6

Conclusion and Future Work

This thesis is motivated by the desire to assist designers with information support for pre assessment in the design phase. The objective is to afford designers an integrative way of accessing and managing information that is used in sustainable design pre assessment. In this chapter, I conclude this dissertation by examining the outcomes of resolving the information management problem rooted in three major research areas: (1) information aggregation; (2) information integration; and (3) design support. Overall, this dissertation is directed towards promoting a general approach using systematic and computational means for solving issues when considering sustainable design pre assessment requirements from rating systems.

Briefly, in this dissertation in Chapter 2, I have laid out the important background work related to previous researches and discussed current applications. This has been followed in Chapter 3 by identification of informational requirements for pre assessment. In Chapter 4, a general approach is described within the proposed framework through the development of a prototype tool to support sustainable design pre assessment. In Chapter 5 a formalized approach to managing and informational requirements is given.

The contributions, current research limitations and future directions are discussed. Contributions are given within the context of the overall framework proposed and technical implementation. Finally, current limitations are discussed and future directions of the proposed with respect to supporting sustainable development in the field of sustainable building design.

6.1 Summary

The following are the main contributions of this dissertation:

Contribution 1: Functional requirements to support the design of sustainable buildings with LEED assessment standard.

Chapter 3 presented the functional requirements that are necessary for sustainable building ratings systems, namely LEED NC 2.1 (all six categories). Requirements elicited in this research comprise of information related to elements in standard building information models that are present, need augmentation or missing; external information that supports sustainable building assessment and information in the form of documents. The body of information was identified from literature, a number of representative rating systems and case studies. The informational requirement of the rating systems from a building information modeling view were organized by phases in a buildings life cycle. Further categorization and description of elements required for sustainable building assessment were created for use by the demonstrated prototype and later formalized to demonstrate a more general approach. In order to query a building information model, relationship between model information and rating system requirements were identified and represented as computable form for the prototype application.

Contribution 2: Integrated approach for supporting sustainable building design assessment

Chapter 4 presents a prototype application that uses the information schema created to support sustainable building assessment. The schema and adapted data structure enables user to choose a rating system, and light-weight building information model for pre assessment. Categories in the rating system can be chosen and for each credit the information is updated in XML based templates that are converted to HTML for viewing. User can input and modify the data entered and run the application again for viewing the results. This process has been demonstrated with selected credits from Water Efficiency and Energy and Atmosphere category for three LEED versions. The adoption of this process shows that the increase of information with the newer versions can be mapped and stored in the current process, however the output formats need to be updated to handle excel files. In the Energy and Atmosphere category

Contribution 3: An approach to managing and using sustainability rating system requirements for design through a building design process

In Chapter 4, the module used in the prototype application for managing rules in a spreadsheet format allows rule sets to be updated as the requirements change with rating system version changes. Information accumulated in the project for pre assessment remains in the COBie file for future use. In addition to this approach for information management and formats for assessment, Chapter 5 presents a formalized approach to organize and manage information that is required for rating system assessment with discussed building information formats (COBie and IFC). The approach described enables a user to query the sustainable information ontology and use it for further development and creation of further applications.

Contribution 4: A general approach in converting rating systems requirements into functional database form for efficient maintenance of computable rules has been used in the NSF project to automate LEED 2009 EAc1 and EAp2 template completion from Energy Plus and eQuest.

6.2 Current Limitations

The work presented here represents the necessary groundwork and integration to building a prototype for sustainable design pre assessment. This development needs to be informed and supported by actual user testing and feedback. Although the prototype has met research objectives, it makes no claim on effectiveness or usefulness in a practical context. The user-friendliness of the prototype tool has not been empirically tested. User tests in actual building design and pre-assessment contexts should be conducted to validate and improve the design of the UI. The implicit work-process governed by the framework design of the tool also needs to be tested. Other issues, notable user-centric issues such as ease-of-use, interpretation of results accuracy, application of results in decisions, are not yet covered by this research.

6.3 Future Directions

This dissertation presents a general approach to solving information support and management for sustainable design assessments. The current implementation is focused on theoretical and technical investigations into the problem. In order to demonstrate the power of utilizing such an approach for sustainable design assessment, more case studies and evolving requirements of sustainability standards need to be considered. In addition, a user-friendlier interface between users and computational mechanisms is expected for the successful integration in the real design practice.

The BUILD research project

There is on-going work being done in an NSF funded SEED_EFRI project called BUILD (Barriers, Understanding, Integration – Life cycle Development). The project uses the techniques used in this research to formulate, store and manage rules in a similar fashion for automating LEED energy template completion by identifying elements from EnergyPlus, and mapping them to LEED 2009 EAp1, EAp2 and EAc1 through an engine developed by the project team. The project includes a user-testing phase to investigate the user-centric issues and applicability of the workflow in actual building design practice. In addition to the NSF project, further mapping between EnergyPlus and LEED Healthcare EAp2, and EAc1 has been carried out. Current work is ongoing for mapping and creating rules sets for LEED v4 EAp2.

Ontology-based sustainable design information management

It is clear that more research is required in formulating ontology for sustainable building. Ontologies can be used to describe the relationships between sustainability elements and building information model elements and parameters. By building a link between sustainability requirements and corresponding design data, it would be possible to query, update design models and manage information formally.

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APPENDIX

Appendix A: Sustainability Pre-Assessment Database

The database for the framework starts with the six main phases of a buildings life cycle. The columns are Phase ID and Phase Name.

Table A1. Main building phases

Phase ID	Phase Name
A	Pre-Design
B	Design
C	Pre-Construction
D	Construction
E	Operation
F	Decommission

Table A2 shows the next level of detail; the phases have categories, which are arranged by columns: Category ID, Category Name and Description. Category A mostly includes Pre-Design activity related elements.

Table A2. Category A

Sub Category ID	Sub Category Name	Sub Category Description
A_1	Person	Name, organization, contact of persons in the team
A_2	OwnerDecision	Owners decisions on project requirement
A_3	TeamDecision	Team decisions on collaboration and project goals
A_4	ContractorDecision	Contractors decisions in meeting project goals
A_5	ProjectInformation	General project information such as building type, location.

Table A3. Sub Category A_1

Credit Element ID	Credit Element Name	Credit Element Description
A_1_1_1	PersonOrgranization	Name of organization of person
A_1_1_2	OccupantType	Type of occupants part time full time, students, residents, visitors, male female

A_1_1_3	Specialist	Name of authorized professionals
A_1_1_4	ProfessionalSignature	Signature of owner/engineer/contractor

Table A4. Detail of Sub Category A_1

Credit Element Name	Credit Element		Revit Element	Ifc Entity	COBie Picklist
	Value	Type			
PersonOrgranization	String	Simple	NA	IfcOrganization	34-65: Organizations
OccupantType	String	Complex	NA	IfcPerson	NA
Specialist	String	Simple	NA	IfcPerson	34-55 14: Professional Support Staff
ProfessionalSignature	String	Simple	NA	IfcApproval	NA

Category B reflects activities during the design phase. These are organized as B_1 (Site) B_2 (Building Systems), B_3 (Material), B_4 (Indoor Environment), B_5 (Energy), B_6 (Water), B_7 (Emissions). Table A5 illustrates the categories in the design phase.

Table A5. Sub Category B

Category ID	Category Name	Category Description
B_1	Site	Regional and project site related information
B_2	Building	Building geometry, space, envelope and systems
B_3	Material	Material reuse, recycled content, source of origin, etc.
B_4	Indoor Environment	Covers acoustic, lighting, thermal, air qualities of the indoor environment
B_5	Energy	Energy performance, renewable and alternate energies
B_6	Water	Outdoor, indoor water use, and water treatment strategies
B_7	Emissions	Emissions to air, water and soil are included here

In Table A6, B_1 (Site), a partial list of subcategories are given. In the table B_1 category has more subdivisions such as B_1_1 (Regional Planning and Land use), B_1_2 (Bio Diversity), B_1_3 (Land Utilization), B_1_4(Alternate Transportation), B_1_5 (Community Density), etc.

Table A6. Sub Category B_1 (partial list)

Category	Sub Category

ID / Name	ID	Credit Element	Description
B_1_01 RegionalPlanningLanduse	B_1_01_01	SitePlanning Integration	Whether site planning is considered with the regional planning
	B_1_01_02	MixedUsedSite	Site with multiple use such as commercial, residential
	B_1_01_03	Neighborhood VicinityPlan	Plan of vicinity with project boundary
B_1_02 BioDiversity	B_1_02_01	AreaVegetated OpenSpace	The area of open space dedicated to vegetation
	B_1_02_02	AreaOpenZoning Requirement	Open Area required by zoning regulations
	B_1_02_03	EcologicalValue Type	Maintain the ecological value of site after construction

Table A7. Detail of Sub Category B_1 (partial list)

Sub Category			Revit Element	IFC Entity	COBie PickList
Name	Value	Type			
SitePlanningIntegration	Boolean	Simple	Site	IfcSite	34-21 17: Planner
MixedUsedSite	Boolean	Simple	Site	IfcSite	34-21 17: Planner
NeighborhoodVicinityPlan	Boolean	Simple	Site	IfcSite	NA
…					
AreaVegetatedOpenSpace	Number	Simple	Site	IfcSite	23-35 20 17 17: Vegetated Covering
AreaOpenZoningRequirement	Number	Simple	Site	IfcSite	NA
EcologicalValueType	Number	Complex	NA	NA	NA

There is further elaboration for certain subcategories where the type is complex. This means that there are more parameters that have to be supplemented. In this example the subcategory Ecological Value shows more information that needs to be acquired for the evaluation for this measure.

Table A8. Detail of Subcategory B_1_02_03 EcologicalValue

SubCategoryID	WeedInfestationArea	BareGroundArea	NativeVegetationArea	ExoticGardenArea	NativeGrazingArea	CropFarming	PlantationForest
B_1_02_03							

The Energy category can be found in the section B_5_1 (Energy Efficiency), B_5_2 (Renewable energy), 5_3 (Alternate Green Energy) and 5_4 (Energy Simulation). As seen in Table A10, most of the energy simulation elements needed are not directly available from the model.

Table A9. Sub Category B_5 Energy (partial list)

Category	**Sub Category**		
ID / Name	**ID**	**Credit Element Name**	**Description**
B_5_1 EnergyEfficiency	B_5_01_01	EnergySimulationType	Energy simulation according to reference
	B_5_01_02	EnergyReductionFrom Base	Reduction in energy use from baseline energy model
	B_5_01_03	EnergyConsumptionBas eline	Total amount of energy required in a year, baseline
	B_5_01_04	EnergyConsumptionDes ign	Total amount of energy required in a year, design
	B_5_01_05	EnergyReductionCost	Based on energy reduction in terms of cost
	B_5_01_06	PeakPowerReduction	Amount of peak power reduction
B_5_2 EnergyRenewable	B_5_02_01	RenewableEnergyType	Type and quantities of power from each time generated on site
	B_5_02_02	RenewableEnergyCost	Cost of renewable energy produced
B_5_4 EnergySimulation	B_5_04_05	WeatherFile	Weather file for the simulation
	B_5_04_06	ClimateZone	Selected climate zone for the simulation
	B_5_04_07	HeatingDegreeDays	Number of heating degree days
	B_5_04_08	CoolingDegreeDays	Number of cooling degree days
	B_5_04_09	HeatingHourLoadsNot MetDesign	Number of hours loads not met in the design case
	…		
	B_5_04_21	BaselineInteriorLighting GasUse0Degree	Baseline Interior lighting, gas usage with model at 0 degree
	B_5_04_22	BaselineInteriorLighting GasUse90Degree	Baseline Interior lighting, gas usage with model at 90 degree
	B_5_04_23	BaselineInteriorLighting GasUse180Degree	Baseline Interior lighting, gas usage with model at 180 degree
	B_5_04_24	BaselineInteriorLighting GasUse270Degree	Baseline Interior lighting, gas usage with model at 270 degree

B_5_04_25	BaselineInteriorLighting GasUseResult	Baseline Interior lighting, gas usage average result

Table A10. Details of Sub Category B_5 (partial list)

Credit Element Name	Value	Type	Revit Element	IFC Entity	COBie PickList
EnergySimulationType	String	Simple	NA	NA	NA
EnergyReductionFromBase	Number	Simple	NA	NA	NA
EnergyConsumptionBaseline	Number	Simple	NA	NA	NA
EnergyConsumptionDesign	Number	Simple	NA	NA	NA
EnergyReductionCost	Number	Simple	NA	NA	NA
PeakPowerReduction	Number	Simple	NA	NA	NA
RenewableEnergyType	String	Simple	NA	NA	NA
RenewableEnergyCost	Number	Simple	NA	NA	NA
…					
WeatherFile	String	Simple	NA	NA	NA
ClimateZone	String	Simple	NA	NA	NA
HeatingDegreeDays	Number	Simple	NA	NA	NA
CoolingDegreeDays	Number	Simple	NA	NA	NA
HeatingHourLoadsNotMet Design	Number	Simple	NA	NA	NA
…					
BaselineInteriorLightingGas Use0Degree	Number	Simple	NA	NA	NA
BaselineInteriorLightingGas Use90Degree	Number	Simple	NA	NA	NA
BaselineInteriorLightingGas Use180Degree	Number	Simple	NA	NA	NA
BaselineInteriorLightingGas Use270egree	Number	Simple	NA	NA	NA
BaselineInteriorLightingGas UseResult	Number	Simple	NA	NA	NA

…

Appendix B: Mapping ratings to framework elements

The framework of elements is used to analyze the priority of elements by listing the credits of chosen rating systems.

BREEAM

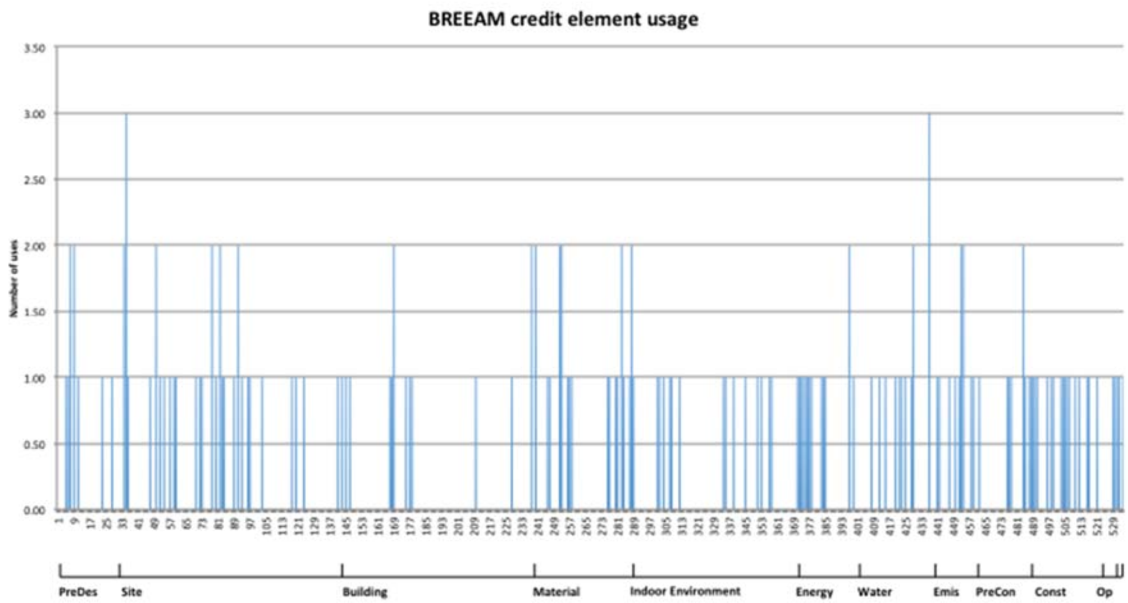


Figure B 1 **Occurrences of BREEAM elements with respect to the framework elements**

Table B1. Highly used elements in BREEAM

ID	NumberLine	Credit Element Name	Uses in BREEAM
B_1_2_3	36	EcologicalValue	3
B_7_1_1	438	CO2EmissionQuantity	3
A_1_1_7	08	AccreditedProfessional	2
A_1_2_2	10	BuildingType	2
B_1_2_2	35	AreaOpenZoningRequirement	2
B_1_2_18	51	SurveyOfHabitat	2
B_1_4_5	79	CoveredandSecureRacks	2
B_1_4_6	80	AdequteLighting	2

B_1_4_9	83	PublicTransportType	2
B_1_4_10	84	FrequencyPublicTrans	2
B_1_4_18	92	RegularTotalParking	2
B_1_4_22	96	FullTimeEmployee (FTE)	2
B_3_1_5	241	ResponsiblySourcedMaterial	2
B_3_8_1	284	LowImpactFullLifeCycle	2
B_7_2_1	454	SustainableDrainage	2
B_7_2_2	455	WaterTreatmentOil	2
D_1_1_1	485	ReduceConstructionWaste	2

LEED 2.1

Table B2 shows a portion of LEED NC 2.1 credits mapped to the required elements. The number of elements required is summed and the priority thus calculated.

Table B2. Framework mapped to credit element occurrences of LEED NC 2.1

	ID	Category Name	ID	Sub Category Name	Usage	LEED2.1				
Decision Making	A_1_2	Owner Decision	A_1_2_2	BuildingType	1.0	LEED EA Pre2				
			A_1_2_3	OccupantType	3.0	LEED WE3	LEED SS4.1	LEED SS4.2		
			A_1_2_4	OccupantNumber	3.0	LEED WE3	LEED SS4.1	LEED SS4.2		
			A_1_2_5	Location	1.0	LEED SS8				
			A_1_2_6	Date						
			A_1_2_7	OwnerProjectRequirement(OPR)	1.0	LEED EA Pre1				
			A_1_2_8	OPRSustainabilityGoalsIdentification	1.0	LEED EA Pre1				
			A_1_2_9	OPREnergyEfficiencyGoals	1.0	LEED EA Pre1				
			A_1_2_10	OPRIndoorAirQualityGoals	1.0	LEED EA Pre1				
	A_1_3	Design Team Decision	A_1_3_1	SustainableGoalsIdentification	1.0	LEED EA Pre2				
			A_1_3_2	CollaborationMeetings						
			A_1_3_3	CollaborationMeetingNumber						
			A_1_3_4	InformationDistribution						
	A_1_4	Contractor Decision	A_1_4_1	Considerate Contractor						
			A_1_4_2	ConstructorSubmittals						
site	B_1_1	Regional planning and landuse	B_1_1_1	SitePlanningIntegration						
			B_1_1_2	MixedUsedSite						
			B_1_1_3	NeighborhoodVicinityPlan						
			B_1_1_4	BuildingPositionEnvResponsive						
	B_1_2	Biodiversity	B_1_2_1	AreaVegetatedOpenSpace	1.0	LEED SS5.2				
			B_1_2_2	AreaOpenZoningReq	1.0	LEED SS5.2				
			B_1_2_3	EcologicalValue (enum)						
			B_1_2_4	AreaNativeVegetation	1.0	LEED SS5.1				
			B_1_2_5	AreaOfDisturbance						
			B_1_2_6	MinimumDisturbance						
			B_1_2_7	DistanceDisturbancePerimeter	1.0	LEED SS5.1				
			B_1_2_8	DistanceDisturbanceWalkway	1.0	LEED SS5.1				
			B_1_2_9	DistanceDisturbanceParking	1.0	LEED SS5.1				
			B_1_2_10	DistanceDisturbanceUtilities	1.0	LEED SS5.1				
			B_1_2_11	DistanceDisturbancePatio	1.0	LEED SS5.1				
			B_1_2_12	DistanceDisturbancePermeable(enum)	1.0	LEED SS5.1				
			B_1_2_13	AreaVegetatedRoof	5.0	LEED SS5.1	LEED SS5.2	LEED SS7.1	LEED SS 7.2	LEED 6.2

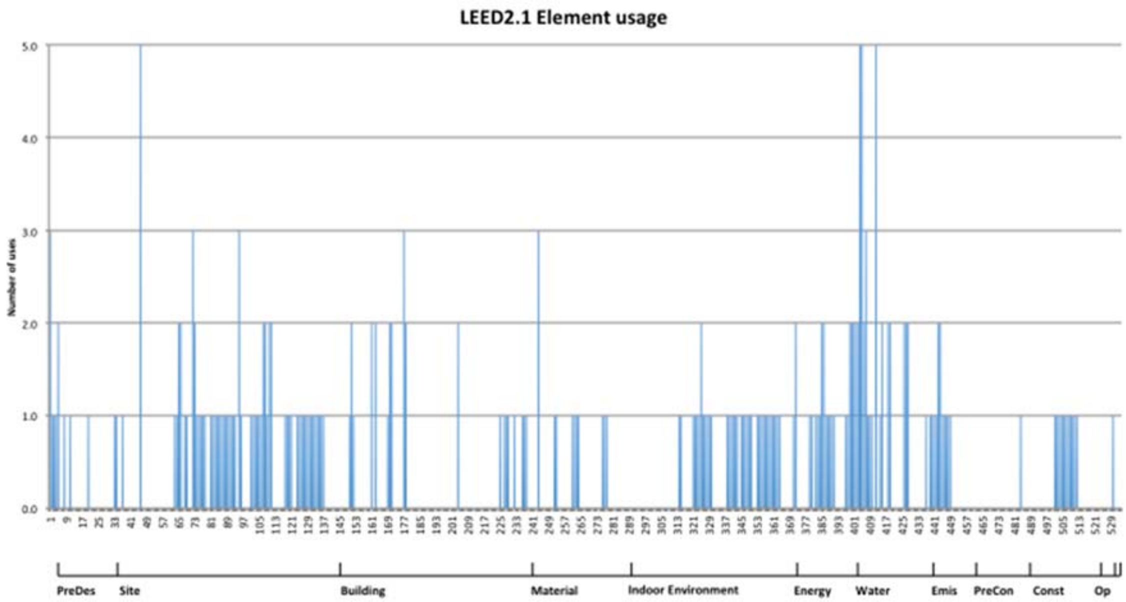


Figure B2 **Occurrences of LEED NC 2.1 elements with respect to the framework elements**

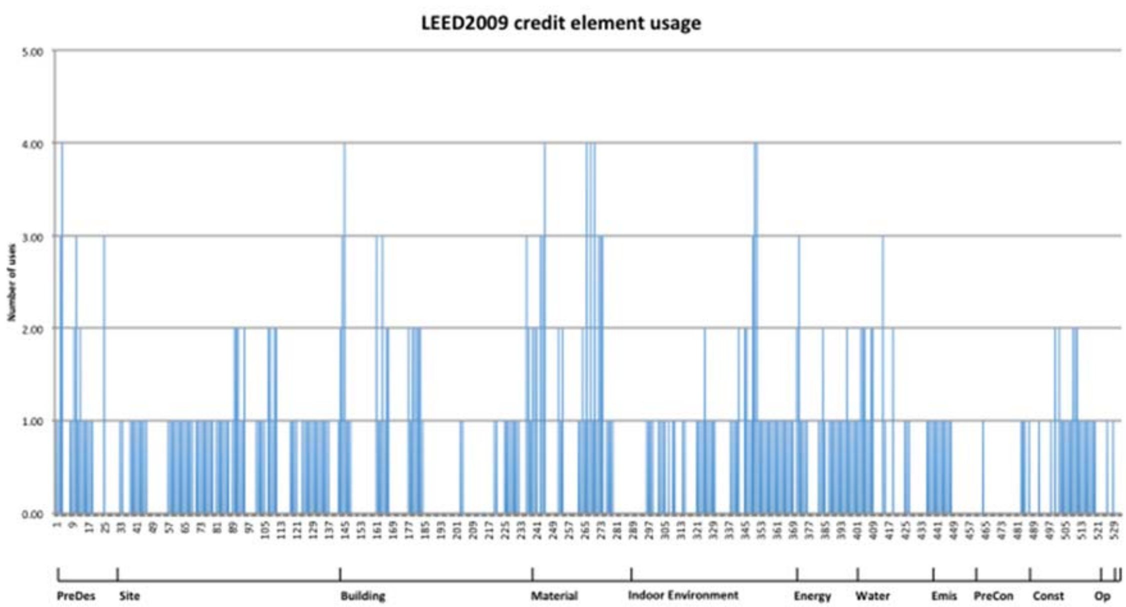


Figure B3 **Occurrences of LEED NC 2009 elements with respect to the framework elements**

Table B3. Framework mapped to occurrences of LEED NC 2009

ID	RefNumber	Credit Element Name	LEED2.1 Use	LEED2009 Use
B_1_2_14	47	AreaVegetatedRoof	5	4
B_6_2_5	413	CapturedRainwaterQuantity	5	3
B_1_4_22	96	FullTimeOccupant (FTE)	3	2
B_2_6_1	178	HVACSystemCompliance	3	2
B_5_1_1	372	EnergySimulation	3	3
B_5_2_3	386	TotalEnergyRequirement	3	3
B_5_2_4	387	TotalEnergyCost	2	2
B_3_1_9	245	MaterialManufacturer	3	4
B_6_1_9	408	VegetationType	3	2
B_6_2_8	416	RecycledWasteWaterQuantity	2	3
B_2_4_6	162	SpaceType	2	3
B_2_4_8	164	OccupiedSpaceArea	2	2

Green Star

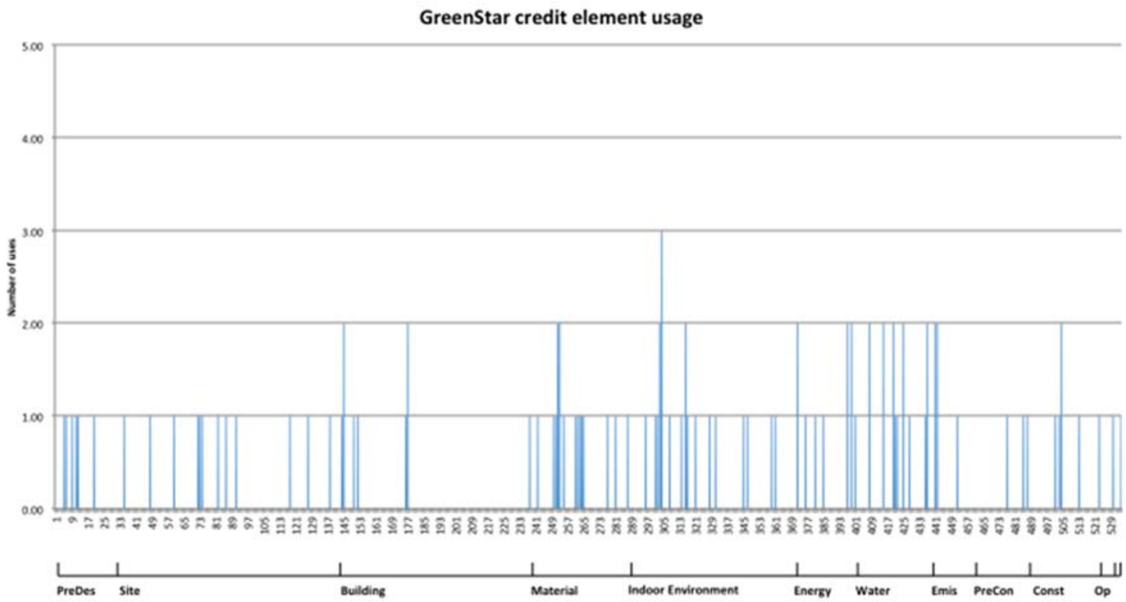


Figure B4 **Occurrences of Green Star elements with respect to the framework elements**

Table B4. Highly used elements in Green Star

ID	RefNumber	Credit Element Name	Uses in Green Star
B_2_6_1	178	HVACSystemCompliance	3
B_4_5_3	305	LightPowerDensity	2
B_3_2_1	253	ReuseFacade	2
B_3_2_2	254	PreAndPostConsumerContent	2
B_4_6_3	317	AutomaticLightingControl	2
B_6_1_1	400	PotableWaterUseQuantity	2
B_6_3_1	421	EfficientWaterFixture	2
B_6_2_8	416	RecycledWasteWaterQuantity	2
B_6_3_6	426	LeakDetectionSystem	2
B_7_1_5	442	OzoneDepletingPotential	2
B_7_1_6	443	OzoneDepletingMaterial	2
D_2_1_4	505	CommissioningPlan	2

CASBEE

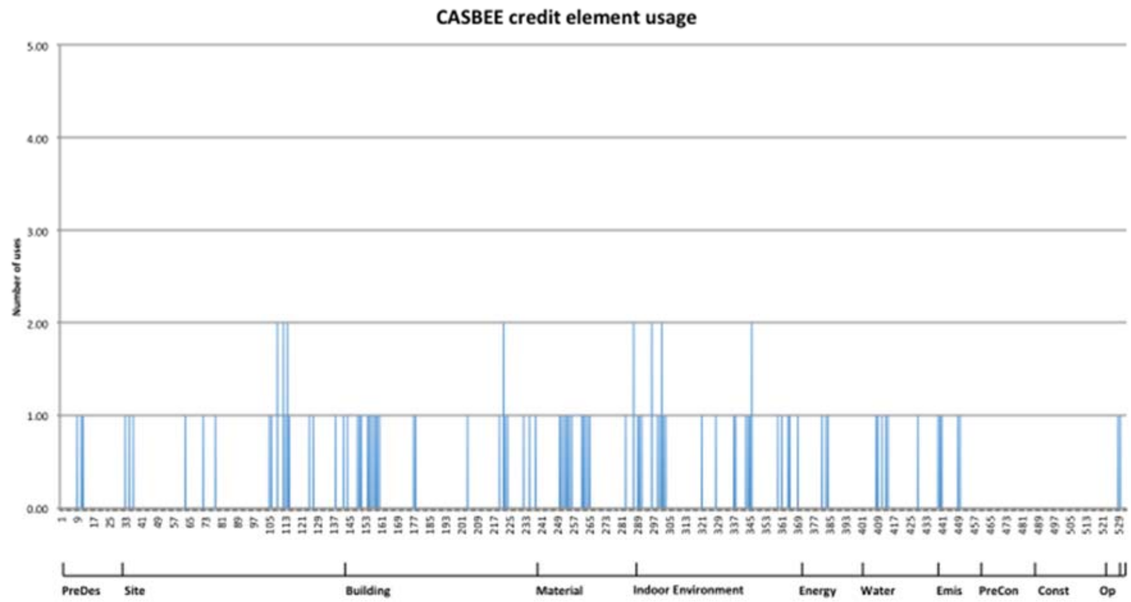


Figure B5 **Occurrences of CASBEE elements with respect to the framework elements**

Table B5. Framework mapped to occurrences of CASBE

ID	RefNumber	Credit Element Name	Uses in CASBEE
B_2_6_3	110	PavingMaterialSRI	2
B_1_6_6	113	VegetationForBufferingWinds	2
B_1_6_8	115	TopographyForWindBuffer	2
B_2_4_1	157	FlexibleSpacePlanning	2
B_2_5_1	170	EnevelopeInsulation	2
B_2_5_5	174	SoundInsulationOfEnvelope	2
B_2_8_2	208	ElectricalSubMetering	2
B_2_9_2	211	EfficientLifts	2
B_4_1_1	288	SoundLevel	2

Green Globes

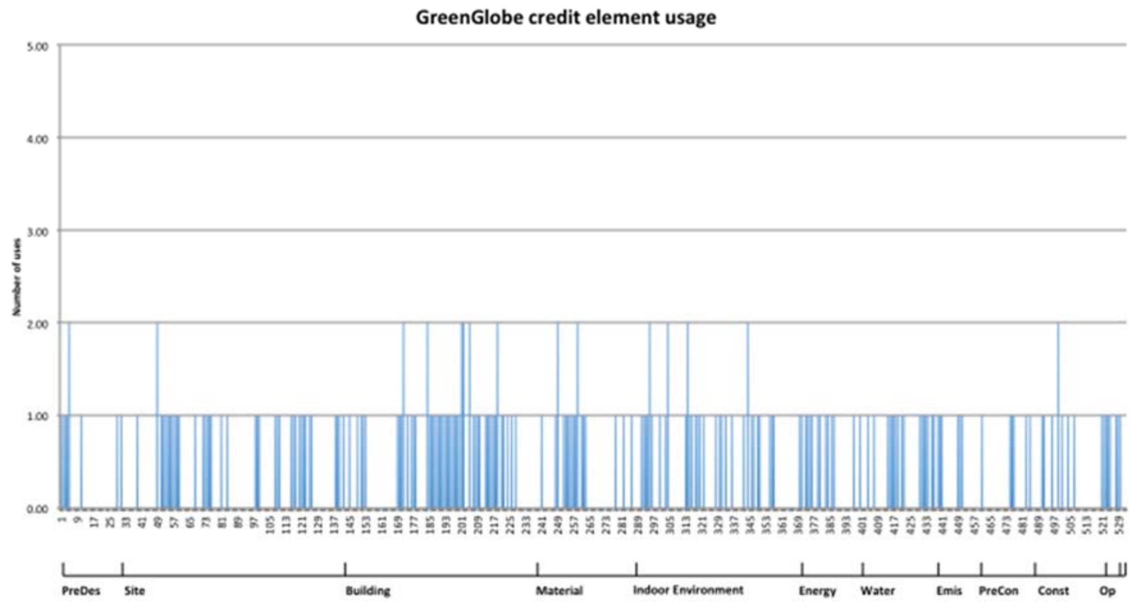


Figure B6 **Occurrences of Green Globes elements with respect to the framework elements**

Table B6. Highly used elements in Green Globes

ID	RefNumber	Credit Element Name	Uses in Green Globes
B_2_5_4	173	EnvelopeWaterLeakage	2
B_4_5_3	305	LightPowerDensity	2
B_2_12_4	229	WindowDistanceFromUser	2
B_3_1_6	242	ThirdPartyCertifiedMaterial	2
B_2_5_1	170	EnevelopeInsulation	2
B_2_5_5	174	SoundInsulationOfEnvelope	2
B_4_7_9	330	DensityOfPeople	2
B_4_8_8	304	MoldControl	2
B_6_2_1	345	WaterFixtures	2
B_7_1_5	442	RefrigerantGlobalWarmingPotential	3

Multiple rating systems

Table B7. Framework mapped to occurrences of multiple rating systems

Phase	Category	ID	Sub Category Name	ID	Credit Element Name	LEED 2.1	LEED 2009	BREEAM	GreenStar	CASBEE	GrGlobes
Predesign	Decision Making	A_1_1	Person	A_1_1_7	CommissioningAgentSignature	1.0	1.00				
		A_1_2	Owner Decision	A_1_2_1	OwnerIntention	1.0	1.00	1.00			1.00
				A_1_2_2	BuildingType		1.00				
				A_1_2_3	OccupantType		2.00				
				A_1_2_4	OccupantNumber		3.00				
				A_1_2_5	Location	1.0	1.00	1.00	1.00		1.00
				A_1_2_6	Date		2.00				
				A_1_2_7	OwnerProjectRequirement(OPR)		2.00				
				A_1_2_8	OPRSustainabilityGoalsIdentification		1.00				
				A_1_2_9	OPREnergyEfficiencyGoals		1.00				
				A_1_2_10	OPRIndoorAirQualityGoals		1.00				
				A_1_2_11	OPREquipmentExpectations		1.00				
				A_1_2_12	OPROccupantExpectations		1.00				
		A_1_3	Design Team Decision	A_1_3_1	SustainableGoalsIdentification	1.0		0.00			1.00
				A_1_3_2	CollaborationMeetings						1.00
				A_1_3_3	CollaborationMeetingNumber						1.00
				A_1_3_4	InformationDistribution						2.00
		A_1_4	Contractor Decision	A_1_4_1	Considerate Contractor			2.00			
				A_1_4_2	ConstructorSubmittals		3.00				
Design	site	B_1_1	Regional planning and land use	B_1_1_1	SitePlanningIntegration						
				B_1_1_2	MixedUsedSite						1.00
				B_1_1_3	NeighborhoodVicinityPlan						
				B_1_1_4	BuildingPositionEnvResponsive					1.00	
		B_1_2	Biodiversity	B_1_2_1	AreaVegetatedOpenSpace	1.0	1.00				
				B_1_2_2	AreaOpenZoningReq	1.0	1.00				
				B_1_2_3	EcologicalValue (enum)			3.00	1.00	1.00	
				B_1_2_4	AreaNativeVegetation	1.0	1.00	1.00		1.00	1.00

Figure B7 gives a graphical depiction of the occurrences of all rating system elements with respect to framework credit elements. The highest occurrence among these elements is the HVAC System that equipment and system requirement with 10. The next group of elements with from 8-9 occurrences include the following: area of vegetated roof, lighting power, luminance level, ventilation effectiveness, energy efficiency, use of captured rainwater, use of recycled waste water, quantity of rainwater, and global warming potential of refrigerants. See Table B7.

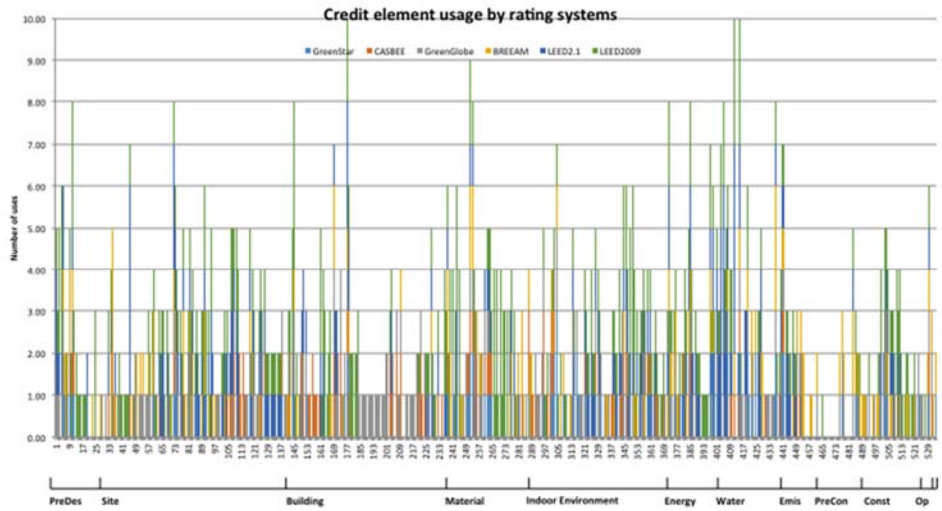


Figure B7 **Occurrences of all rating system requirements with respect to the credit elements**

Table B8. Highly used elements by all rating systems (more than 8 occurrences)

ID	RefNumber	Credit Element Name	Combined Uses
B_2_6_1	178	HVACSystemCompliance	10
B_6_2_5	413	CapturedRainWaterQuantitiy	10
B_6_2_8	416	RecycledWasteWaterQuantity	10
B_3_2_1	253	MaterialReuse(enum, beam, floor, door, furniture, etc)	9
A_1_2_4	12	OccupantNumber	8
B_1_3_16	73	SiteArea	8
B_2_2_3	146	BuildingGrossArea	8
B_5_1_1	372	EnergySimulationType	8
B_5_2_3	386	TotalEnergyRequirement	8
B_5_1_2	405	ReduceEnergyFromBase	8
B_3_2_2	254	PreAndPostConsumerContent	8
B_6_1_7	414	UseRecycledWasteWater	8
B_7_1_1	438	CO2EmissionReductionDesign	8

In the next tier are elements that occur 6 to 7 times; there are fifteen such elements. See Table B9 and Table B10 for a sample of elements that are used 5 times. These are followed by credit elements that are required fewer times (one to four). The least used credit elements are those used only by a specific rating system.

Table B9. Highly used credit elements by all rating systems (6- 7 occurrences)

ID	RefNumber	Sub Category Name	Combined Uses
B_1_2_13	47	VegetatedAreaRoof	7
B_2_5_1	170	EnevelopeInsulation	7
B_4_5_3	305	LightPowerDensity	7
B_5_4_1	398	SimulationNumber	7
B_6_1_6	413	UseCapturedRainwater	7
B_6_3_1	421	EfficientFixtures (dry, composting toilets, occupant sensors)	7
B_7_1_5	442	RefrigerantGlobalWarmingPotential	7
B_7_1_6	443	RefrigerantOzoneDepletingPotential	7
B_3_1_3	239	CertifiedWood	6
B_3_1_9	245	MaterialManufacturer	6
B_4_9_1	346	VentialtionRate	6
B_4_9_6	351	IncreasedVentialtionRate(natural)	6
B_6_1_1	400	PotableWaterQuantity	6
B_6_2_1	409	WaterFixtures (enum-watercloset, urinal)	6
E_1_4_1	531	BuildingUserGuide	6

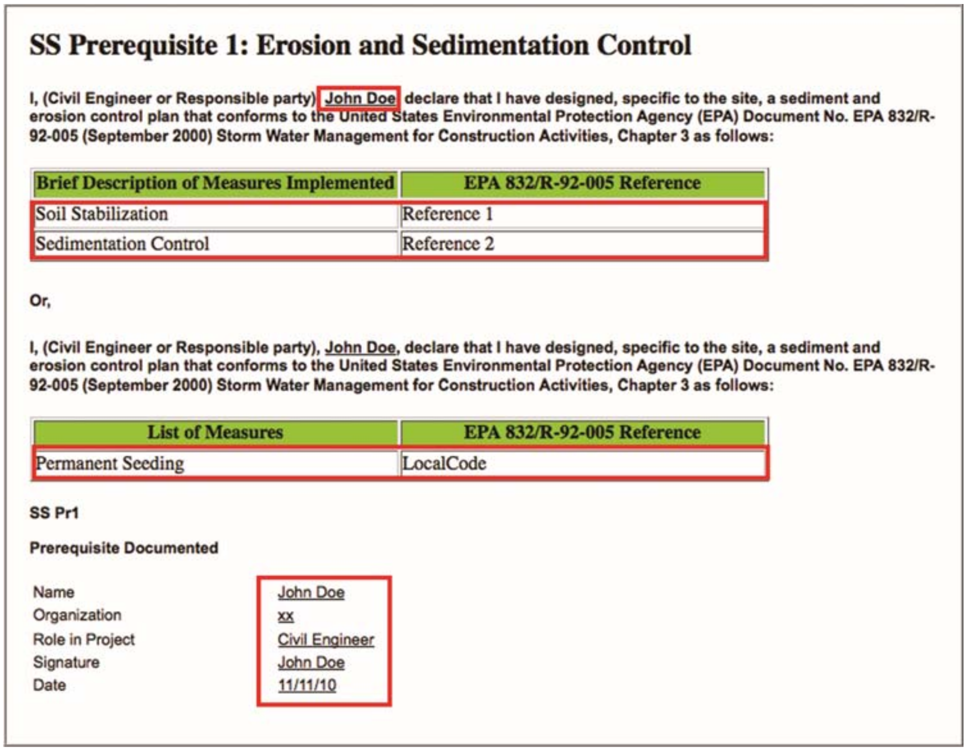
Table B10. Sample credit elements by all rating systems (5 occurrences)

ID	RefNumber	Sub Category Name	Combined Uses
B_1_4_5	82	CoveredandSecureRacks	5
B_1_4_22	96	FullTimeOccupant (FTE)	5
B_1_6_1	108	VegetationForSunControl	5
B_1_6_2	109	ShadeInXyears	5
B_1_6_3	110	PavingMaterialSRI	5
B_1_6_4	111	RoofSRI	5
B_2_2_2	145	BuildingFootprintArea	5
B_2_4_6	162	SpaceType	5
B_2_12_4	229	WindowDistanceFromUser	5
B_3_6_2	262	PaintsCoatingsVOCLimit	5
B_3_6_3	263	CarpetSystemVOCLimit	5
B_4_3_1	297	DaylightedSpacePercentage	5

Appendix C: COBie to LEED sample template output

LEED NC 2.1

Sustainable Site credit SSp1: Erosion and Sedimentation Control



SS Prerequisite 1: Erosion and Sedimentation Control

I, (Civil Engineer or Responsible party) John Doe declare that I have designed, specific to the site, a sediment and erosion control plan that conforms to the United States Environmental Protection Agency (EPA) Document No. EPA 832/R-92-005 (September 2000) Storm Water Management for Construction Activities, Chapter 3 as follows:

Brief Description of Measures Implemented	EPA 832/R-92-005 Reference
Soil Stabilization	Reference 1
Sedimentation Control	Reference 2

Or,

I, (Civil Engineer or Responsible party), John Doe, declare that I have designed, specific to the site, a sediment and erosion control plan that conforms to the United States Environmental Protection Agency (EPA) Document No. EPA 832/R-92-005 (September 2000) Storm Water Management for Construction Activities, Chapter 3 as follows:

List of Measures	EPA 832/R-92-005 Reference
Permanent Seeding	LocalCode

SS Pr1

Prerequisite Documented

Name	John Doe
Organization	xx
Role in Project	Civil Engineer
Signature	John Doe
Date	11/11/10

Figure C 1. **SSp1: Erosion and Sedimentation Control**

Comparison of Sustainable Sites credit information requirement over LEED 2.1, LEED2009 and LEED v4.

Sustainable Sites	Credit Description	LEED 2.1	LEED 2009	LEED V4
SSp1	Construction Activity Pollution Prevention	8	10	8
SSp2				7
SSc1	Site Selection	10	12	7
SSc2	Development Density and Community Connectivity	13	7	12

SSc3	Brownfield Redevelopment	12	5	10
SSc4.1	Alternative Transportation: Public Transportation Access	13	11	15
SSc4.2	Alternative Transportation: Bicycle Storage and Changing Rooms	9	14	16
SSc4.3	Alternative Transportation: Low Emitting and Fuel Efficient Vehicles	8	16	12
SSc4.4	Alternative Transportation: Parking Capacity	9	14	11
SSc5.1	Site Development: Protect or Restore Habitat	11	13	18
SSc5.2	Site Development: Maximize Open Space	11	14	12
SSc6.1	Storm-water Design: Quantity Control and quality control	11	13	13
SSc7.1	Heat Island Effect: Non-Roof and Roof	5	17	19
SSc8	Light Pollution Reduction	8	25	18

Water Efficiency

WE Credit1.1: Water Efficient Landscaping, Reduce by 50%

I, (Architect, HVAC Engineer, Civil Engineer, Environmental Advisor, Ecologist or Responsible party), Harriett Shupp, declare that potable water consumption for site irrigation has been reduced by 50% through:

☐ **High efficiency irrigation technology**

OR

☑ **No permanent irrigation system**

OR

☐ **Captured rain or recycled water.**

I have provided the following to support the declaration:

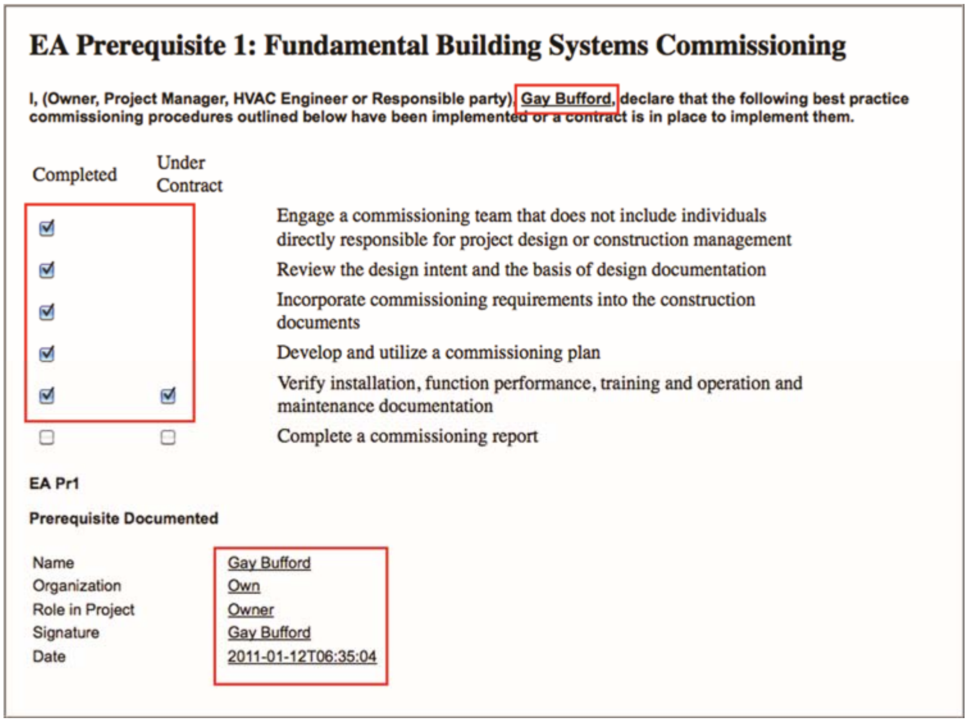
☑ **A brief narrative of the equipment used and/or the use of drought-tolerant ot native plants.**

WE Cr 1.1 (1 point): Water Efficient Landscaping, Reduce by 50%

Points Documented

Name	Harriett Shupp
Organization	Engineering
Role in Project	Civil Engineer
Signature	Harriett Shupp
Date	2011-01-12T06:35:04

Figure C 2 **WEp1, Water Efficient Landscaping**



EA Prerequisite 1: Fundamental Building Systems Commissioning

I, (Owner, Project Manager, HVAC Engineer or Responsible party), Gay Bufford, declare that the following best practice commissioning procedures outlined below have been implemented or a contract is in place to implement them.

Completed	Under Contract	
☑		Engage a commissioning team that does not include individuals directly responsible for project design or construction management
☑		Review the design intent and the basis of design documentation
☑		Incorporate commissioning requirements into the construction documents
☑		Develop and utilize a commissioning plan
☑	☑	Verify installation, function performance, training and operation and maintenance documentation
☐	☐	Complete a commissioning report

EA Pr1

Prerequisite Documented

Name	Gay Bufford
Organization	Own
Role in Project	Owner
Signature	Gay Bufford
Date	2011-01-12T06:35:04

Figure C 3 **EAp1, Fundamental Building Systems Commissioning**

Materials and Resources

MR Prerequisite 1: Storage and Collection of Recyclables

I, (Architect, Interior Designer or Responsible party), Lonnie Files, declare to USGBC that an easily accessible area of appropriate size has been dedicated to serve the recycling needs of the entire building and the separation and storage area for recycling will accomodate the following materials (at a minimum):

- [x] **paper**
- [x] **corrugated cardboard**
- [ ] **glass**
- [x] **plastics**
- [ ] **metals**

I have provided the following to support the following declaration

- [x] **a plan showing the area(s) dedicated to recycled material collection and storage**

MR Prerequisite: Storage and Collection of Recyclables

Documented

Name	Lonnie Files
Organization	Architects
Role in Project	Architect
Signature	Lonnie Files
Date	2011-01-12T06:35:04

Figure C 4 **MRp1, Storage and Collection of Recyclables**

Environmental Air Quality

EQ Prerequisite 1: Minimum IAQ Performance

I, (HVAC Engineer or Responsible party) Matt Erik, declare that the project is fully compliant with ASHRAE 62-1999 and all approved Addends published at the time of LEED project registration.

- [x] **Have provided supporting documentation describing the procedure employed in the IAQ analysis (Ventialtion Rate Procedure)**

EQ Pr1

Prerequisite Documented

Name	Matt Erik
Organization	Engineering
Role in Project	HVAC Engineer
Signature	Matt Erik
Date	2011-01-12T06:35:04

Figure C 5 **EQp1, Minimum IAQ Performance**