

# FROM DESIGN TO PRE-CERTIFICATION USING BUILDING INFORMATION MODELING

Tajin Biswas,<sup>1</sup> Tsung-Hsien Wang,<sup>2</sup> and Ramesh Krishnamurti<sup>3</sup>

## ABSTRACT

*Designs which address sustainability requirements are becoming increasingly desirable, as the objectives of sustainable design reduce resource depletion of energy, water, and raw materials; prevent environmental degradation caused throughout their lifecycle; provide safe, comfortable and healthy living environments. Currently, sustainability in the building domain is judged against standards codified in rating systems. That is, design choices are validated, by measuring design performance against criteria specified by the rating system. Advances in building technologies, design and evaluation tools, and government policies together with tools to benchmark sustainability have created the momentum which fuels an increasing trend towards sustainable building design. However, certification is expensive. It is labor intensive, involving large volumes of data aggregation and information accounting, which, despite the best of intentions, often become a deterrent to designers and the design process. Compliance with a sustainability rating system is not mandatory; increasingly, it is becoming a goal that many designers and authorities would like to achieve. In turn, this demands a cost lowering improvement to the certification process. Since designers mainly tend to employ commercial design tools, it becomes imperative to create a general approach that utilizes information already available in digital form and combine it with rating system information requirements. The challenge lies in identifying informational requirements from rating systems, representing them in computable forms, mapping them to information available from a commercial design tool and evaluating the performance of the design. In this paper we present an overall framework for organizing, managing, and representing sustainability information requirements; to demonstrate an approach to integrating sustainability evaluations in a design environment. We employ a commercially available building information modeler and a sustainable building rating system to develop a process that bridges sustainability assessment requirements with information from the model for pre-evaluation prior to submission for certification. This will enable designers, owners, contractors and other professionals to communicate strategies and make informed decisions to achieve sustainability goals for a project.*

## KEYWORDS

sustainable design rating system, building information model, sustainability assessment, certification

<sup>1</sup>Doctoral candidate, School of Architecture, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA15213-3890. Contact: tajin@cmu.edu

<sup>2</sup>Lecturer in Sustainable Digital Design, Sheffield School of Architecture, The University of Sheffield, Arts Tower, Western Bank, Sheffield S10 2TN, UK. Contact: tsung-hsien.wang@sheffield.ac.uk

<sup>3</sup>Professor, School of Architecture, Carnegie Mellon University. Contact: ramesh@cmu.edu

## INTRODUCTION

Architecture presents a unique challenge in the field of sustainability. Construction projects typically consume vast amounts of materials, produce tons of waste, and require lots of energy for heating and cooling. In the United States, buildings consume 73% of all the electricity; 40% of raw material, 13.6% of all potable water and produce 38% of all carbon dioxide emissions (USGBC 2011). Given the magnitude of effects that the building industry has on environmental quality, utilizing sustainable design philosophy decisions at each phase of a design process will reduce negative impacts on the environment and provide a healthy work space for occupants, without compromising the bottom line (GSA).

It is our contention that in architecture this notion of sustainability be applicable to buildings of every kind--retrofit, new, tall and small structures, corporate office or humble residence. Moreover, this notion of sustainability should be irrespective of cost, design, process, or implementation. There are several ways of targeting sustainability in buildings, for example, through a pragmatic approach and well-managed processes (Williams 2010). Sustainability is affected, among other issues, by site, density, climate, construction practices and cultural factors. For the purpose of this paper, we take a conventional approach, that is, we resort to an authority such as LEED (Leadership in Energy, and Environmental Design), BREEAM (Building Research Establishment's Environmental Assessment Method), or an appropriate sustainable building rating system in certifying a building as sustainable (Cole 1999, Gissen 2003). In order to ensure that new buildings can be certified as sustainable, it is essential to take appropriate steps to automate the process of gathering the information necessary for assessment and pre-certification.

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 and Bradley 2008). Design tools such as building information models (BIM) have paved the way for developing, storing, and updating design data (Krygiel and Bradley 2008). According to the National BIM Standard Project Committee, 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 and Edgar 2008). Additionally, these digital design tools offer possibilities of utilizing the data throughout the design process. Computation of available data allows for query, design, and pre-evaluation of requirements, and for the generation of required forms for final evaluation. It is also our contention that in order to promote the practice of sustainability at a larger scale, technology available through commercial design tools should be utilized to a much greater extent in order to alleviate the costs of design, evaluation and submission.

In order to facilitate a process where computer aided design for green buildings is both feasible and accessible, it is essential to be able to identify and represent building elements, building objects, and their parameters whose informational needs are required in the evaluation of the performance of a design from the standpoint of sustainability. For example, computational methods for energy, lighting, and airflow simulation were established long before the emergence of building information models. It is likely that these performance analyses tools will be embedded in future versions of primary BIM tools (Eastman *et al.* 2008). However, much of the work, apart from performance simulations, required for rating system certification

is ordinarily carried out manually with information stored disparately. This process becomes cumbersome for designs, stored in traditional CAD formats where information relating to building geometry cannot be readily accessed. The survey by Wu and Issa (2010) shows that in present-day green building design efforts current BIM solutions facilitate communication, information exchange and submission submittals.

In this regard, we have developed a framework to organize requirements for sustainable building rating systems. To demonstrate this framework we have developed proof-of-concept prototypes, which integrate requirements with design information. This has enabled us to develop a general approach of using information from commercial BIM software for sustainability assessment. There are four steps in the development:

- Exploring sustainability rating systems and their informational needs
- Identifying and organizing building information for query
- Providing necessary information and conduct assessments that can be used to guide user towards pre-certification
- Creating submission ready templates for evaluation

## **BACKGROUND**

### ***Design tools for sustainable buildings***

A sustainable (or green) building rating system takes into account environmental and other impacts of building design, construction, and operation. According to Fowler and Rauch (2006), a 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 against other buildings. There are now a large number of rating systems deployed to evaluate sustainable architecture. The Building Research Establishment (BRE) was the first to develop a method, BREEAM, for assessing impact on the environment (BREEAM 2012). Subsequently, other countries adopted the BRE approach in developing their own assessment method (Reed 2010). In 1998, in the United States, the US Green Building Council launched LEED (USGBC 2006).

Among current tools, building information models provide a repository of information that are available for sustainable building assessments; however, "not all information is directly accessible within a BIM model itself; therefore, data needs to be exported to another application or imported from a external data source" (Krygiel and Bradley 2008). Current research using commercial BIM and LEED requirements have demonstrated the feasibility for semi-automated evaluation (AlWaer *et al.* 2008, Barnes and Castro-Lacouture 2009, Krishnamurti *et al.* 2010, Biswas *et al.* 2012). In these studies, additional information required for sustainability evaluation are added either by linking to external databases, or by augmenting the model using the capabilities of the BIM software to store additional information.

There are increasingly more projects being registered for LEED certification (Parr and Zaretsky 2010). In response, the US Green Building Council has released a 'LEED automation' tool, which manages and standardizes documents for view and submission (USGBC 2010). However, there is still a need for tools, for use by designers and others, which takes into consideration building information in conjunction with sustainability requirements whether for pre-certification assessment or for managing building operations.

Sustainability assessments are evaluated by using a number of ‘measures’ both qualitative and quantitative. Quantitative measures are easier to encode. Qualitative criteria of assessments are harder to do so as they are subject to evaluation from unbiased third parties (Nguyen *et al.* 2010). Methods to reach quantification of measures vary from one rating system to another. Fowler and Rauch (2006) evaluated five sustainable building rating systems from a selected group that were considered for use in US General Services Administration (GSA) projects. Keysar and Pearce (2007) compare rating systems according to the selection of decision support tools. Table 1 compares a range of rating systems from several countries. The table illustrates how various sustainability-related categories are organized and specifies the kind of (qualitative and quantitative) information required by each. Table 1 is organized according to general assessment areas, which are listed in the left-most 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 site, water use, energy use, materials and resource use, and indoor air quality as the main categories by which to measure environmental impacts. However, there are interesting observations that can be gleaned from Table 1. 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, the Deutsche Gesellschaft für Nachhaltiges Bauen, water use is accounted for in Ecological Quality (DGNB 2012). Likewise, the assessment area Transport is accounted for as ‘Alternate Transportation’ under the LEED Sustainable Sites category, whereas in DGNB it is considered as ‘Public Access’ under the Socio-cultural and Functional Quality category. This shows the difficulty posed when trying to uniformly classify sustainability related information.

## METHODOLOGY

### *Sustainability Evaluation of Buildings using BIM*

In order to illustrate pre-certification of a design according to a sustainability rating system, we selected an exemplar primary rating system and exemplar commercially available BIM software. The assumption here is that once a ‘credit element’ requirement is mapped to ‘BIM elements’ in the building information model, it can then be used in an assessment of the design. As the name implies, a credit element is an entity that is required for the evaluation of a certain sustainability credit, for scoring a point towards certification. 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, for example, area, volume and so on. As an example, the 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 can represent ‘community’ buildings are BIM elements with appropriate attributes such as site area and building area.

For automated evaluation, to integrate requirements between a rating system and the building information model, a mapping between credit elements and BIM elements has to be established. However, not all required BIM elements are to be found in a building information model. There are two possibilities for specifying new BIM elements: firstly, the definition of existing BIM entities (objects) can be extended, or secondly, new BIM entities can be defined. This necessitates augmenting the building information model by identifying

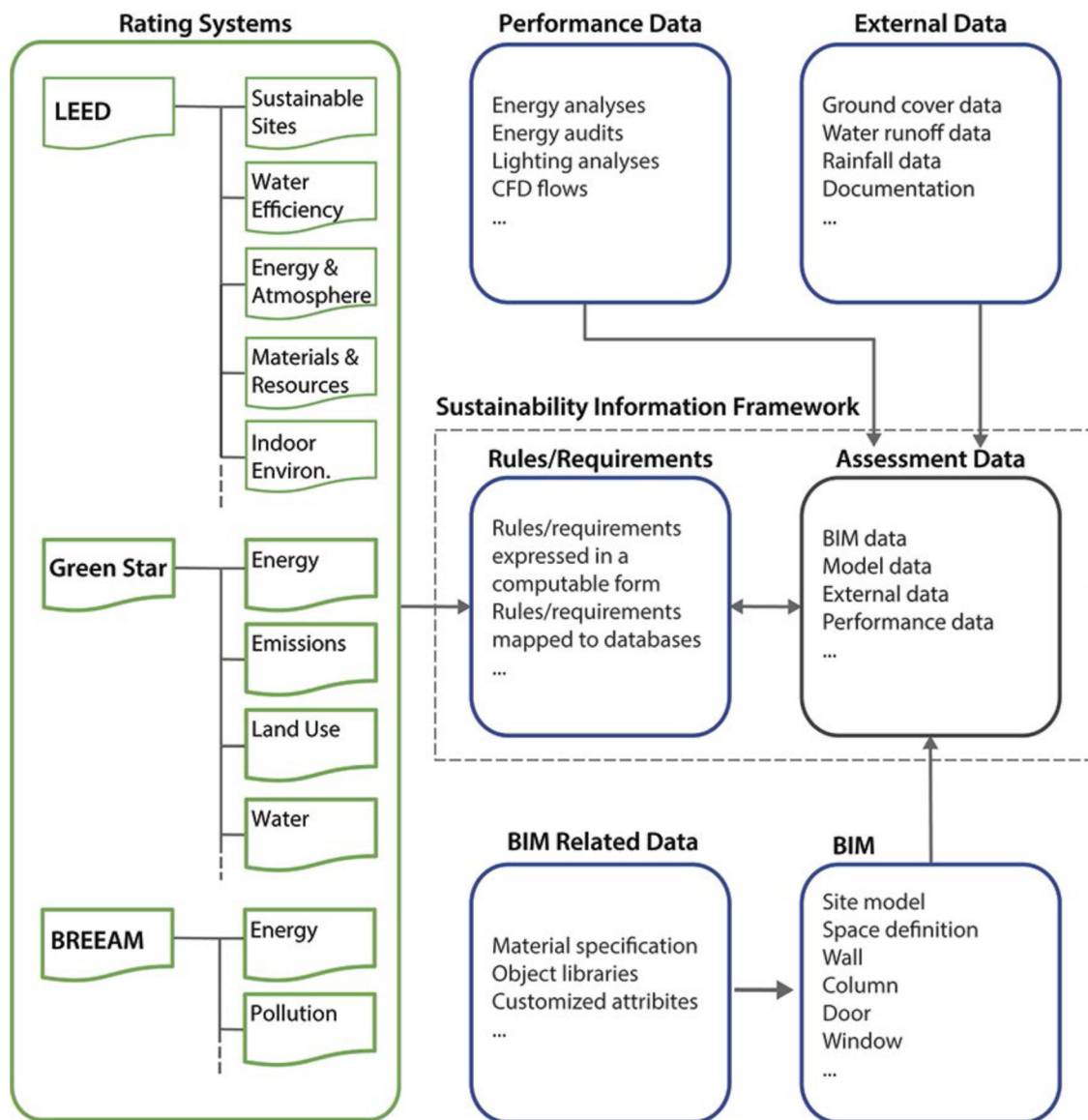
**TABLE 1.** A comparison of seven sustainable building rating systems

Assessment Area	North America		Europe		Asia		Australia
	LEED NC 3.0	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 ( <i>Alternate transport</i> )	Site Selection	Land use	Quality of Location	Site Aspects ( <i>Local transport</i> )	Outdoor Environment/ site	Land use
5 <i>Transport</i>			Transport				Transport
6 <i>Water Efficiency</i>	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 <i>Water Conservation</i>	Materials
10 Innovations	Innovations				Innovations		Innovations
11 Ecology			Ecology	Ecological Quality ( <i>Water</i> )			
12 Economic Benefit		Economic Aspects		Economical Quality			
13 Culture and Heritage		Cultural and Perceptual Aspects		Socio-Cultural and Functional Quality ( <i>Public access</i> )			



additional BIM elements with the possibility of accommodating the required data in external databases. Figure 1 illustrates a framework of information flow between the rating systems that are represented by assessment requirements, BIM elements found in major BIM tools (Eastman, Teicholz, et al. 2008), and performance data and external data. Data for assessing requirements comprise external data, performance data, and BIM and building model related data. The entire list of assessment areas for each rating system is given in Table 1. External data is often not a part of the model, but needs to be present for various assessments; examples include rainfall data, vegetation type 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

**FIGURE 1.** Sustainability information framework. (Assessment areas for the various rating systems are listed in Table 1.)



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 (EERE 2011). Additionally, there is a model related to dependent data, which is inherently integral to and augments the data in the building information model. These include necessary BIM element attributes that are not currently in the model such as occupancy data, custom attributes such as material type, plumbing fixture flow rates, and so on.

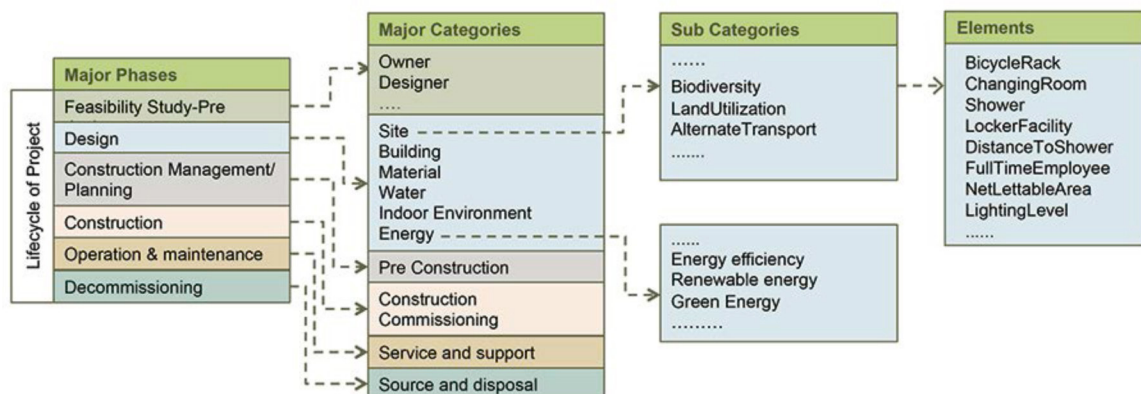
Both performance and external data rely on quantitative and/or qualitative measures. Quantitative measures reflect numerical values, for instance, annual energy use, water consumption, greenhouse gas emissions, volume of reused material and so on. Quantitative data can be measured, modelled, or a combination of both (Todd and Fowler 2010). On the other hand, qualitative measures employ comparative measurements such as the impact of ecological value (Nguyen *et al.* 2010), or rely on user attestation that certain procedures have been followed. This process takes time and effort to input data, which vary in interpretation between different professionals (AlWaer *et al.* 2008).

### Organization of Information

We adopt a grounded theory approach to organizing rating information requirements. Grounded theory states that through an iterative process of data collection, analysis and interpretation, information can get grounded into context and thus lead to theory formation (Glaser and Strauss 1967). For organization of informational requirements the building life cycle is considered generically—we adopt the naming classification by Geilingh (1988) who proposes a life cycle according to transition points. The periods between transitions, termed phases, are of greater interest. There are six phases: Feasibility, Design, Pre-Construction Planning, Construction, Operation & Management and Decommissioning. Temporal in nature, each phase suggests general components and activities that occur during that period of a building project. Figure 2 shows the organization of the sustainable building information.

Subcategories comprise elements that are required for assessment by the rating system. Credit elements in the 'element' category are mapped to BIM elements in the chosen modelling software and also contain the other elements necessary for evaluation. Credit elements may correspond to real model elements/objects or their attributes. They may also correspond

**FIGURE 2.** Sustainable building information structure.

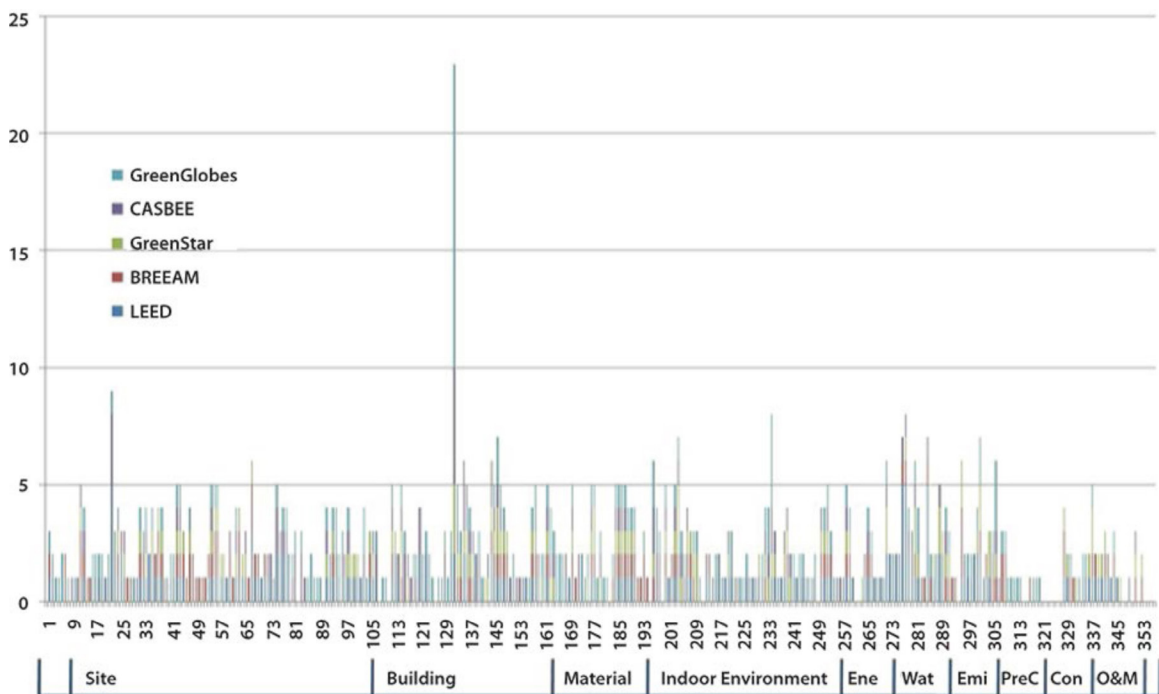


to quantities derivable by calculation from the real model elements in which case, we may consider the model element to be augmented with additional attributes to specify the BIM element. Credit elements may correspond to entities external to the modelling software, but associated with real model elements, for example, flow rates of a plumbing fixture element, or the shading diameter of a plant element. Again, we consider the real model object to be augmented to specify the BIM element. Lastly, the credit element may correspond to an entirely new BIM element or quantity that is not associated with any existing entity, for example, occupants with attributes such as occupants- working full-time or part-time, ground cover with all its attributes such as ground cover type e.g., grass, shrub, paved etc.

Primary testing of the element list was carried out to identify information that is readily available from a typical building information model—tests were carried out in Revit Architecture 2009<sup>®</sup> and subsequently in Revit Architecture 2010<sup>®</sup>. Figure 3 illustrate results on usability of the information in determining elements required for evaluation for five rating systems, namely, LEED 2.1, BREEAM, CASBEE, Green Star and Green Globes. The X axis shows the elements according to their numerical id in the framework, and the height of the Y axis indicates the number of times that particular element is referenced (used). The elements are classified as i) existing in the BIM; ii) can be extended; or iii) external elements and tables required for evaluation. The graph does not distinguish between qualitative or quantitative elements. Elements of greater interest are those used more often or are used by more than one rating credit.

The peak in the graph in Figure 3 corresponds to HVAC related elements in the framework. That is, elements numerically with the highest usage belong to HVAC systems. These elements are used in both energy and indoor air quality related sub-categories. Examples of quantitative measures include energy efficiency and the amount of green house gas emissions. Examples of qualitative measures relate to whether the systems are easy to maintain, replace,

**FIGURE 3.** Occurrences of elements from five rating systems.





**TABLE 2.** Elements prioritized according use in rating systems (between 6 to 8 times).

Framework Elements	Occurrence	Availability in Revit	gbXML Element
AreaVegetatedRoof	8	Roof	Area
LightingSystem	8	Light	LightingSystem
IlluminanceLevel	8	Light	Illuminance
EffectiveVentilation	8	Equipment	IntEquip
ReduceEnergyFromBase	8	NA	Yes (multiple)
UseCapturedRainwater	7	NA	No
UseRecycledWasteWater	7	NA	No
CapturedRainwaterQuantity	7	NA	No
GlobalWarmingPotential	6	NA	Refrigerant Type

operate and monitor. Table 2 lists the next group of elements, which are referenced among 6 to 8 instances. These are 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 refrigerant. The next tier of elements includes those referenced between 3 to 5 times. The last tier corresponds to elements that are referenced specifically by a single rating system.

### ***Sustainability Information Framework Development***

The sustainability information framework (SIF) is developed through analyzing an exhaustive list of data requirements from several rating systems. The information requirements are organized in categories and subcategories for the rating systems and grouped by measures necessary for related sustainability evaluations. A representative list of categories and consequently subcategories have been developed through investigations of the different rating systems, mainly, for new construction commercial building types primarily focusing on requirements in the design phase. In its own right, the framework can be used as a decision-making matrix, “as seen in existing 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 2006).

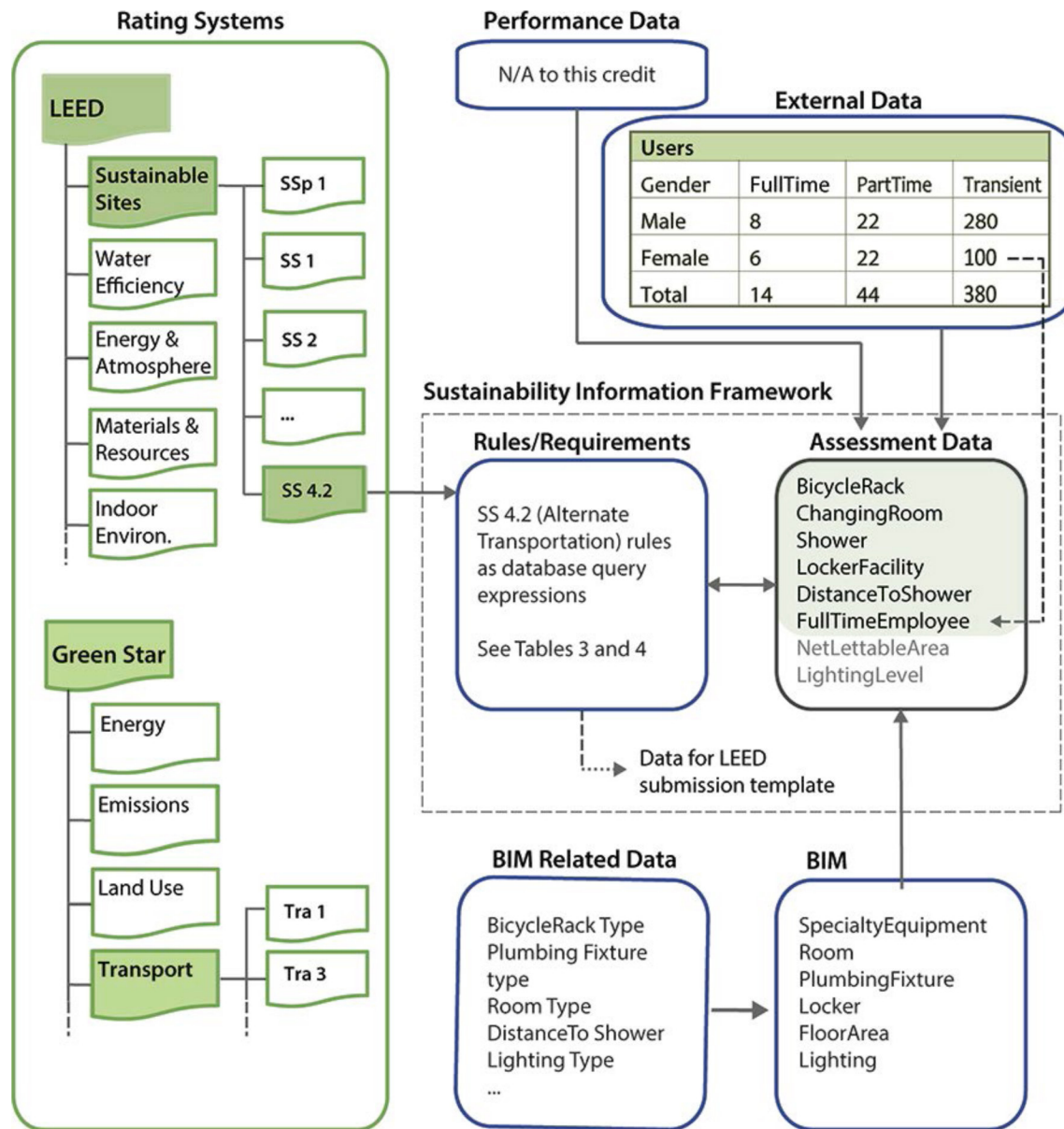
Figure 4 illustrates and demarcates the elements used in evaluating the subcategory, ‘Sustainable Sites,’ credit 4.2 (Alternate Transportation) for generating LEED submission data. For purposes of illustration, LEED NC 2.2<sup>4</sup> is the chosen exemplar primary rating system. In this particular instance, Revit Architecture 2010<sup>5</sup> is the exemplar commercial BIM software, and the BIM elements correspond to Revit elements.

The SIF elements are mapped to appropriate available BIM elements, checked for available attributes, and as required, augmented or supplemented. To evaluate LEED sustainable sites credit SS 4.2, the following information is required: number of male and female users, types of users: full time and part time; the type and number of plumbing fixtures—necessary attributes include the number of uses etc. Bicycle racks are listed under ‘Specialty Equipment’

<sup>4</sup>We began this research in 2007 when LEED 2.2 was the current rating system used in the US. Since then we have been working on updating the work to LEED 2009.

<sup>5</sup>We presume that other BIM software produce very similar results (Wu and Issa 2010).

**FIGURE 4.** Mapping rating system requirements (in this case LEED SS 4.2) to elements in a BIM.



for this particular BIM. Plumbing fixtures are listed under ‘Unique Objects’ in the BIM—these have to be customized with the attributes mentioned. Occupant numbers may be stored in the BIM project, or in an external database with other information. The figure illustrates this information as residing as external data. Rules are interpreted as database (in this case, spread sheet) expressions: queries and functions. For example LEED rules are broken down into simple operations such as ‘SUM-summation’, DIV-division’, ‘MUL-multiplication’, ‘COM’-compare values. Here, the SS 4.2 rules aggregate information from the model, which are then visualized as LEED submission template data. Table 3 shows an example of aggregation of values for evaluation.

Note that Figure 4 also illustrates that the sustainability information framework may include other assessment data related to alternate transport, which is not used in evaluat-

ing SS 4.2. It also highlights the category under Green Star, where a similar sort of credit is evaluated.

Table 3 shows actual data from a case study, in spreadsheet format. The first column holds the unique ID of the value retrieved or processed for use in other calculations. Type indicates the function to be called. Some values are retrieved directly, like the bicycle stand number, others like the name of professional need to be aggregated—these correspond to values residing in different places in the database. The Output column shows the values retrieved from the data structure. Note that the calculation in the row with id LEEDSS-F006, includes full time male occupant number (LEEDSS-F005); this number is obtained from the values shown in Table 4. LEEDSS-F012. Similarly calculates the same information for full time woman occupants, also obtained from pre-processed data. The extent of automating pre-certification depends on the availability of required information for assessments.

**TABLE 3.** Sample LEED rules for SS 4.2 Alternate Transportation Assessment.

ID	Type	Implementation		Output
		Condition	Value	
LEEDSS-0079	Directw Aggregation	(Contact.Category == Architect)	Contact.GivenName + Contact.FamilyName	Jane Adams
LEEDSS-F006	SUM	Null	SUM (LEEDSS-F004, LEEDSS-F005)	100
LEEDSS-F0012	SUM	Null	SUM (LEEDSS-F010, LEEDSS-F011)	80
LEEDSS-0080	SUM	Null	SUM (LEEDSS-F006, LEEDSS-F012)	18
LEEDSS-0081	Direct	(Type.Category ==Transport) && (Type.Description == BicycleStand_Secured)	Type.Number	12
LEEDSS-0082	Direct	(Type.Category ==Transport) && (Type.Description == ShowerAndChanging)	Type.Number	9
LEEDSS-F006	MUL	Null	MUL (0.05, LEEDSS-0080)	9
LEEDSS-0083	COM	Null	(LEEDSS-0081 > LEEDSS-F006)? True: False	True

**TABLE 4.** Pre-processed data to calculate certain values in Table 3.

ID	Type	Implementation		Output
		Condition	Value	
LEEDSS-F001	Direct	Type.Name == MaleOccupantPart	Type.Number	20
LEEDSS-F002	Direct	Attribute.RowName == MaleOccupantPart	Attribute.Value	2
LEEDSS-F003	MUL	Null	MUL (LEEDSS-F001, LEEDSS-F002)	40
LEEDSS-F004	DIV	Null	DIV (LEEDSS-F003, 8)	5
LEEDSS-F005	Direct	Type.Name == MaleOccupantFull	Type.Number	95

## PROTOTYPE DEVELOPMENT

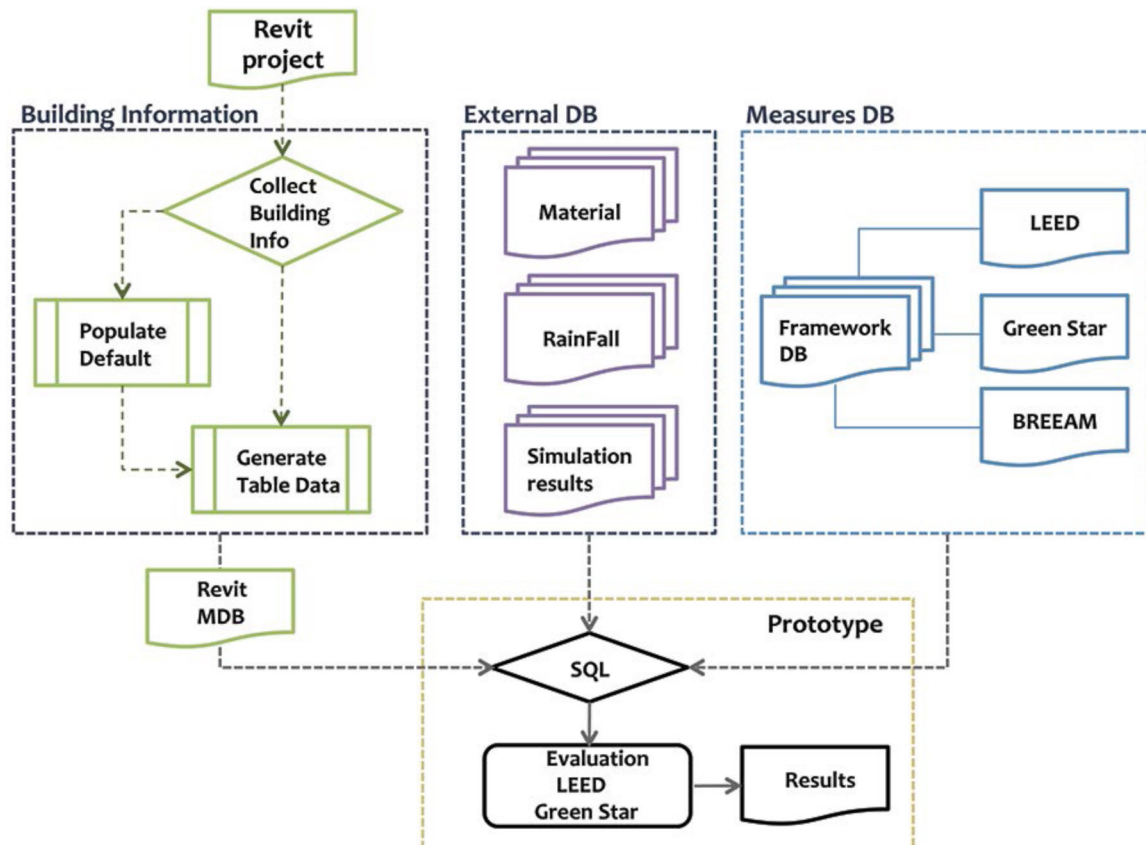
Two prototypes were implemented.

### Prototype 1

The first proof-of-concept prototype was developed to integrate data and calculations from the building information model with rating system requirements. The purpose is to assess the effectiveness of automated evaluation of rating system credits with a given building information model and to determine the extent to which the building information model needs to be augmented and supplemented. Our focus in developing the prototype is to explore how users might interact with the evaluation process. Information flow for the prototype is shown in Figure 5.

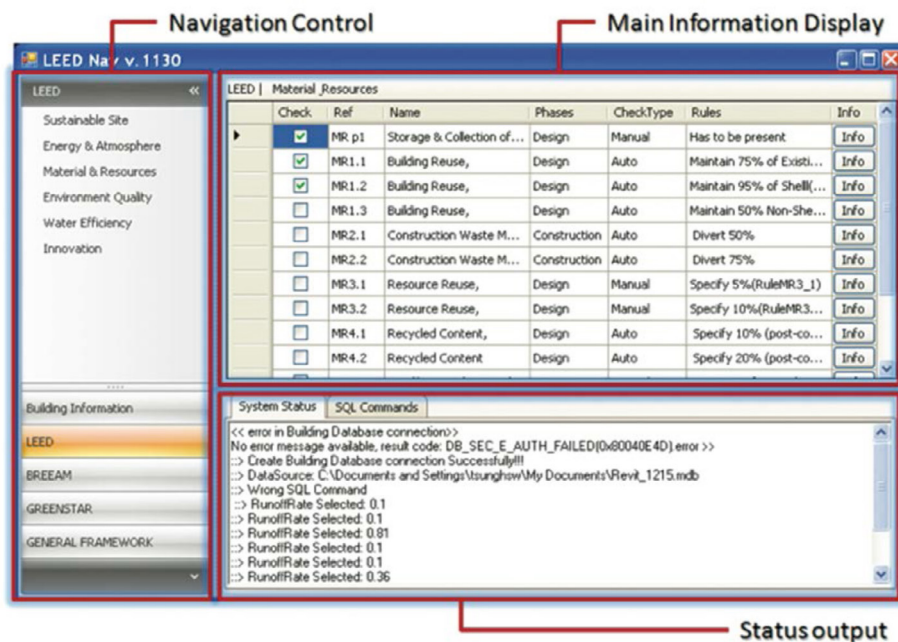
The prototype is built as an external command application on top of Revit. The prototype employs a unidirectional approach using databases generated from the building information model, instead of creating new or modifying existing building elements through the Revit application-programming interface (API). To ensure that the mapping and query are seamlessly integrated, standards and building elements are organized in a database format, data management techniques and SQL commands are used to access information. However, SQL commands are internal to the prototype and are not accessible to the user. Therefore, changes, and updates are handled by internal functions. On the other hand, the database approach provides for an implementation, which is effective in data management.

**FIGURE 5.** Information flow in the prototype.

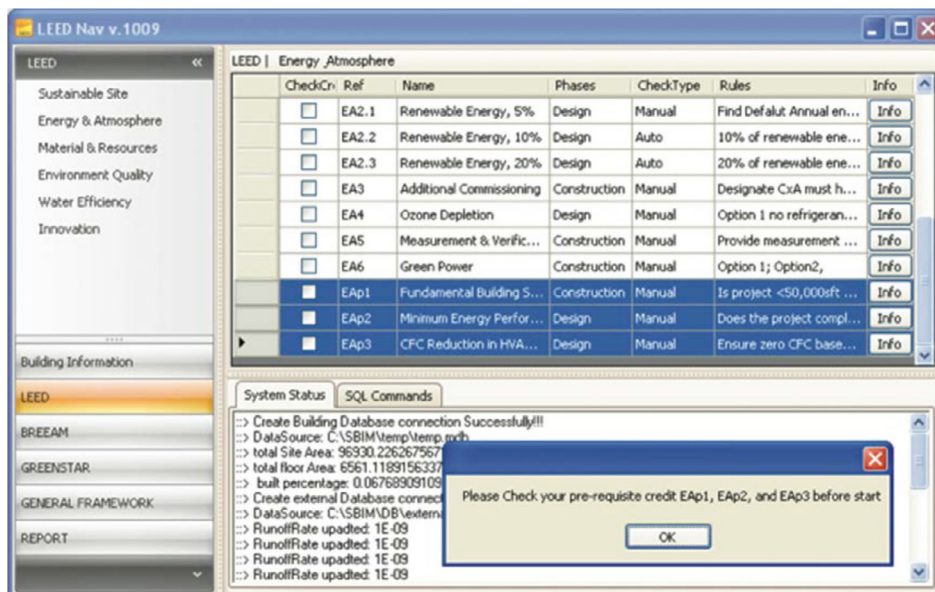


The interface of the prototype has three main panels: navigation control on the left, main information display on the right, and status output at the bottom. See, for example, Figure 6. An evaluation starts once the user has checked the prerequisite credits. For proof-of-concept we assume that the user ensures that all prerequisite requirements have been met. Next, the prototype retrieves and temporarily stores model information in a database in order to evaluate the credits for the currently selected rating standard, say, LEED as shown in the example illustrated in Figures 6 through 9.

**FIGURE 6.** Prototype user interface showing: (right) rating systems (upper left) main information display and (lower left) status output.

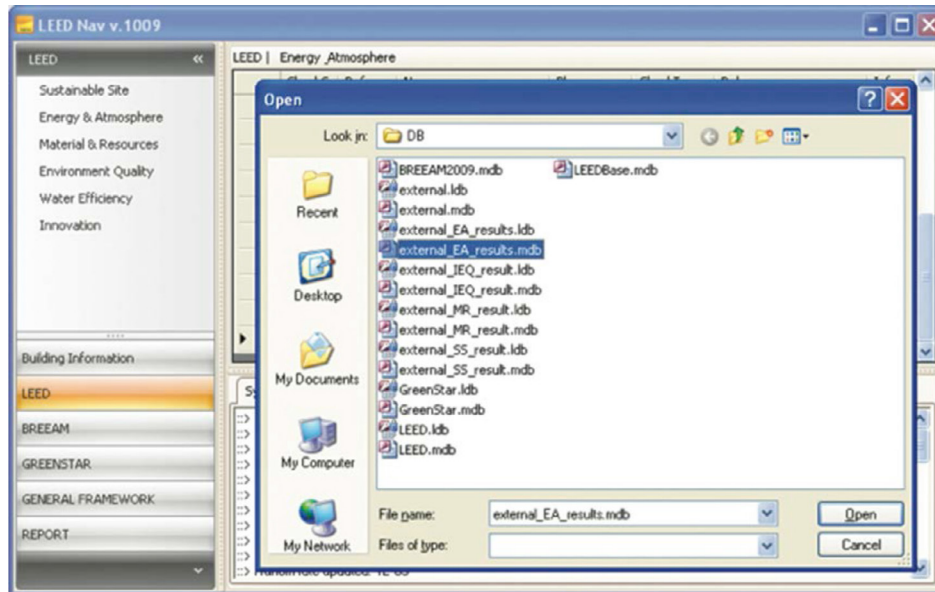


**FIGURE 7.** Prerequisite credit checking for EA category (user check before any evaluation).

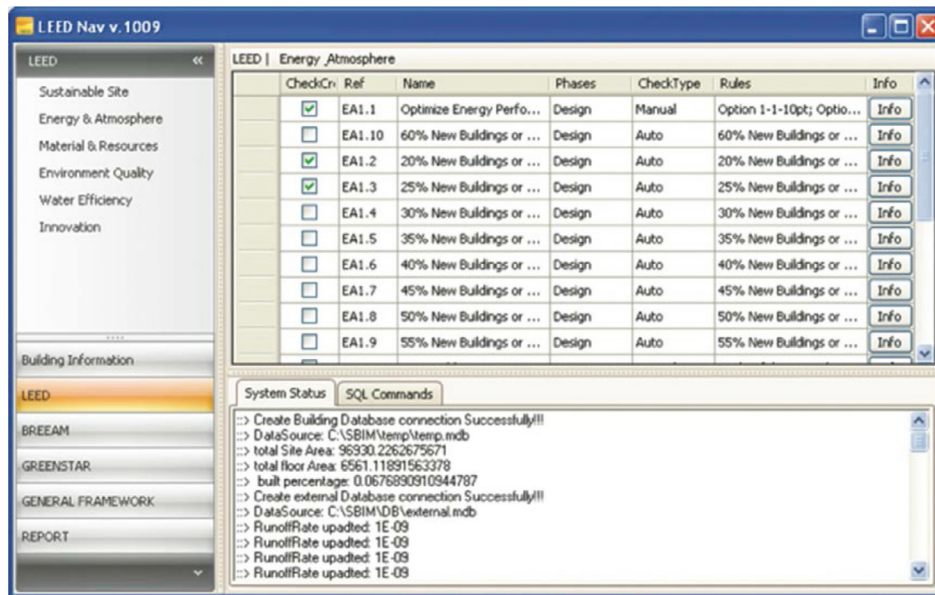




**FIGURE 8.** Providing additional simulation results by uploading saved databases for evaluation.



**FIGURE 9.** Credit evaluation of EA category from the uploaded databases.



There are three types of evaluations performed by the prototype: i) using information directly from the model; ii) using information from the model with augmented BIM elements and external databases; and iii) using information from the model, external databases and simulation results. Figure 8 illustrates the situation where simulation results have to be provided. The simulation results are collected in a database prior to their use in an evaluation. The prototype aggregates the information from all sources, namely, the building information

**FIGURE 10.** LEED rating result as a graph.



model, simulation results and the rating standard; the results are evaluated and updated to an internal data table. The evaluation result can be displayed in one of three different formats: as a table, as an image (graph) (see Figure 10), and as an html file. These results provide users with the current status of the project.

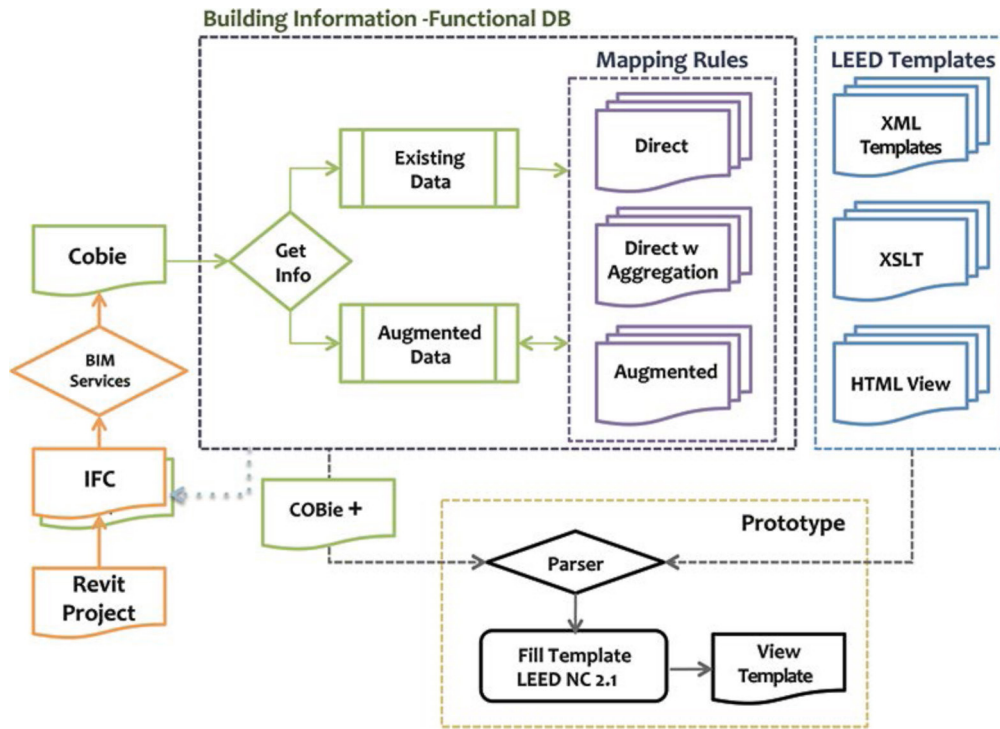
### **Prototype 2**

The second prototype follows the idea of accumulating information from a building information model, augmenting necessary data for assessment from the framework, and mapping LEED rules for query and assessments. The purpose of this prototype is to prepare submission ready templates for USGBC by the creation of a functional database that explicitly enables the mapping and update between rules, building elements and XML templates. Figure 11 shows the process of sharing information from a general BIM to fill LEED templates. For this prototype we exported Revit project data into IFC, and then converted it to a structured table (i.e., spreadsheet). For convenience, the Construction Operations Building Information Exchange (COBie) was chosen for this format (East 2011). COBie offers a structure that can be used, extended and augmented; moreover, semantically it provides lightweight access to IFC data.

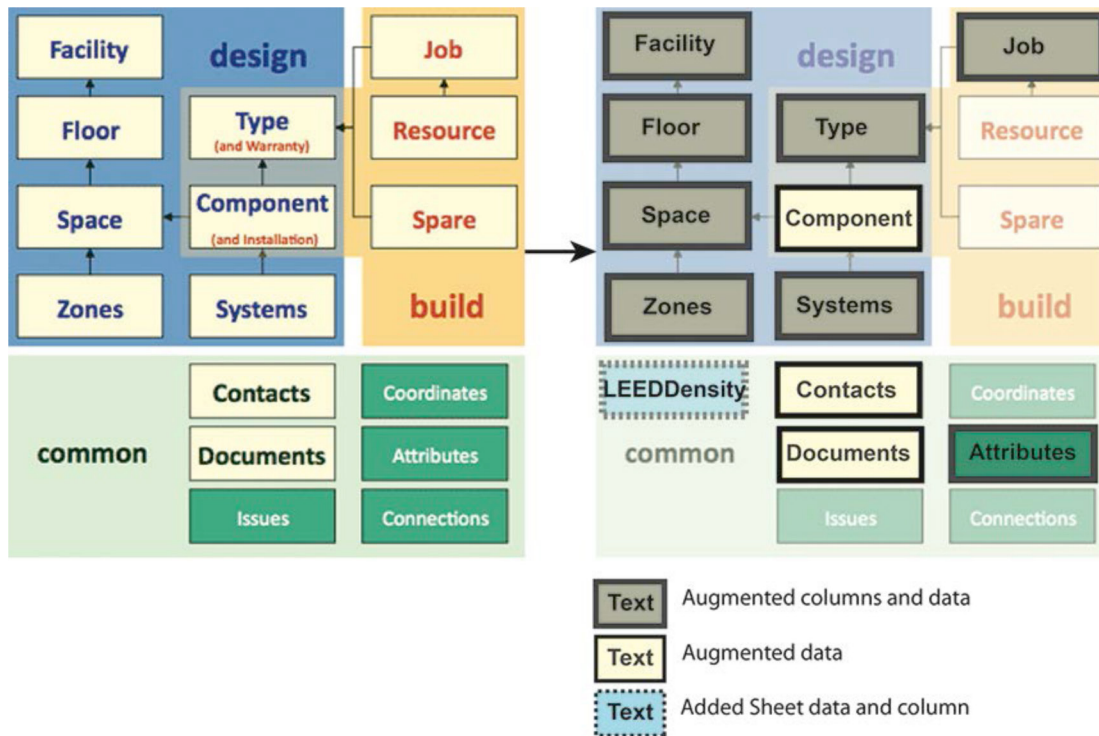
To identify the data types required for LEED evaluation, we established a mapping between LEED queries, COBie elements and the corresponding XML templates. COBie data have been classified and identified as ‘Direct’, ‘Direct with Aggregation’, and ‘Augmented.’ Direct data exists in COBie and can be directly queried. Direct with Aggregation refers to data in COBie that is requires aggregation from one or multiple COBie sheets in order to satisfy a LEED query.

Figure 12 illustrates both the original COBie derived from the IFC data and its augmented data model necessary to support LEED queries. The left side illustrates how information is provided through COBie. Its data begins with a listing of *facilities* (i.e. buildings or projects), each of which has *floors*, which within each are *spaces*, typically rooms in the interior and functional spaces in the exterior, such as “parking lot” or “patio seating.” For spaces to perform as intended specific *systems* made up of *components* are required. The *types* of systems include: electrical, heating, ventilating and air conditioning (HVAC), potable water, wastewater, fire protection, intrusion detection and alarms and other systems. In COBie, there is at least one system for each facility. Components and types are specified during installation or build.

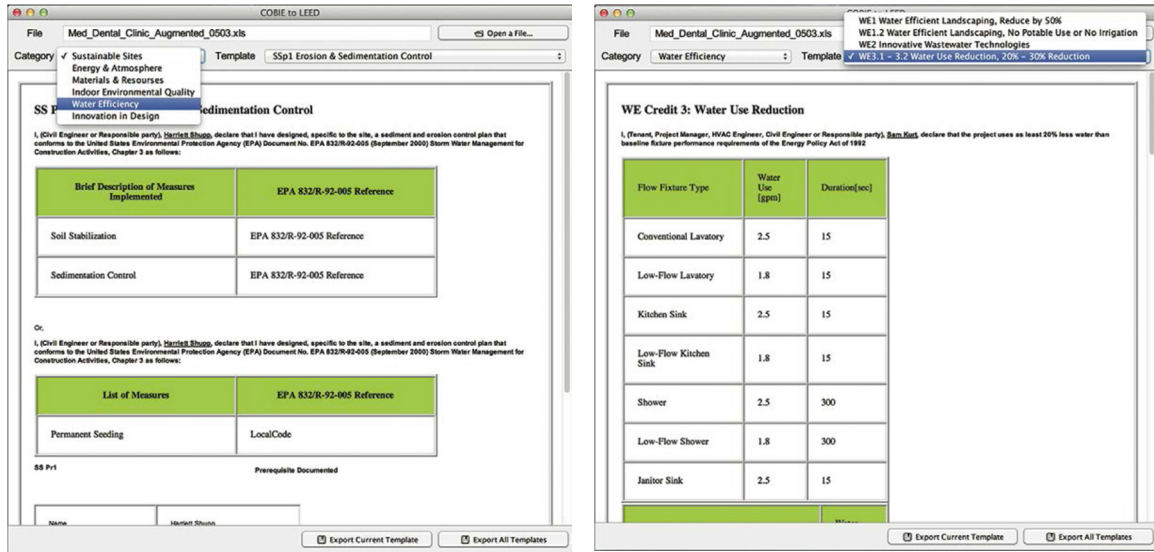
**FIGURE 11.** Converting pre-assessments to LEED submission templates.



**FIGURE 12.** Illustrating the augmentation of COBie for LEED. (Source for the COBie diagram on the right: East, 2011: Figure 5.)



**FIGURE 13.** Converting pre-assessments to LEED submission templates LEED 2.1.



The COBie data model is represented as a spreadsheet with each element considered as a sheet. A new sheet, LEEDDensity, is added to the database. Sheets such as Attributes, Facility, Type, Space, Systems, and Job have added columns with new fields and rows of data. The sheets Floor, Contacts, Component and Documents retain their original columns but have rows with additional data. For example in the Contacts sheet, LEED assessment needs the 'Architect', 'Civil Engineer', 'Contractor', 'Commissioning Agent' to fulfil credit evaluation. In this case it is necessary for the user to be aware that this particular element is queried and therefore requires it to be filled with appropriate information.

There is a difference in evaluating for rating credits (Prototype 1, Figure 6) versus explicitly and automatically filling submission templates (Prototype 2) with direct data, processed data, and augmented data. Augmented data by its very nature is a combination of additionally required project data and a list of documents. In LEED the submission of certain documents are required for evaluation. In this stage we use documents with unique identifiers to represent user inputs. The viewer allows the user to choose an example project for pre assessment, and save the selected templates that are filled.

Figure 13 illustrates the filled templates for the LEED category, sustainable sites prerequisites and when the user chooses the LEED category, water efficiency, along with water credits 3.1 and 3.2. Currently the user interface is limited to selecting the project database file and the LEED templates to be filled. We envision more capabilities in the next version of the prototype where the model selected will be checked for completeness and default data sets can be used as placeholders in the model.

## CASE STUDY

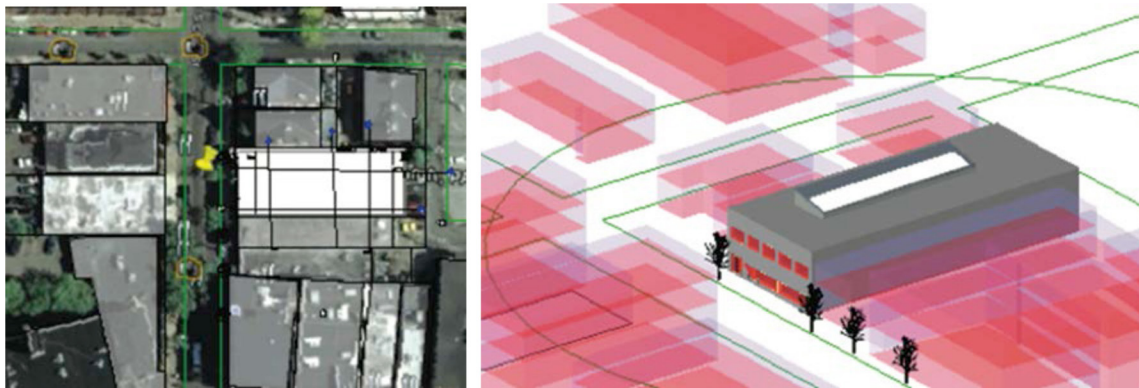
The first prototype determines how well the automated assessment process compares to assessment that is manually carried out. The second prototype assesses the effectiveness of the building information model for automated submissions. The two prototypes were tested on the same LEED Silver-certified building as a building case study.



**FIGURE 14.** Solar panels (left), Floor plan (right).



**FIGURE 15.** Test Case, Site plan and massing (left), 3D view (right).



The test case study building is a two-story, 11,000-square-foot structure located in Pittsburgh (Figure 14) and includes a skylight on the second floor for natural lighting and a 25-kilowatt solar cell array on its roof to help power the facility. Figure 15 (left) shows an overlay of the site with Google maps to create a mass model for the site. The assessment is based on the building information model, created for the project, together with augmented information and simulation results from the simulation software.

## **RESULTS FOR PROTOTYPE 1**

### ***Sustainable Sites***

Table 5 shows the credits achieved by the prototype. The prototype achieved 3 out of 6 credits in the Sustainable Sites category. The nature of the data, for example, direct data in the BIM, or from an external source is color-coded.

Sustainable site credits relating to water are achieved using an external landscape database. However, there is a noticeable problem, which arises when determining whether the project has fulfilled the landscaping criteria requirements. To resolve the user needs to specify the different types of vegetated site area needed for automatic calculation. This is a feature lacking in the current Revit model. To bridge the gap, 'landscape zoning' could be used to divide the site into calculable gardening zones so that, by using the external landscape database, the evaluation can be automated. The prototype lacks the functionality to create and



**TABLE 5.** Results achieved using the prototype in the Sustainable Site Category. (Achieved and Prototype).

Certified Case Practice	General Prototype	LEED Category & Subcategories <i>Sustainable Sites</i>	Points
<b>6</b>	<b>3</b>		<b>14</b>
Y	–	Erosion & Sedimentation Control	Required
1	0	Site Selection	1
1	1	Development Density	1
0	0	Brownfield Redevelopment	1
		Alternative Transportation:	
1	0	▪ Public Transportation Access	1
1	1	▪ Bicycle Storage & Changing Rooms	1
0	0	▪ Alternative Fuel Vehicles	1
1	0	▪ Parking Capacity and Carpooling	1
		Reduced Site Disturbance:	
0	0	▪ Protect or Restore Open Space	1
0	0	▪ Development Footprint	1
		Storm water Management:	
1	1	▪ Rate and Quantity	1
0	0	▪ Treatment	1
		Landscape & Exterior Design to Reduce Heat Island:	
0	0	▪ Non-Roof	1
0	0	▪ Roof	1
0	0	Light Pollution Reduction	1

	Achieved by only using existing BIM elements
	Requires extensions to existing BIM entities and external data
	Requires new BIM elements and external data
	Requires simulation results/reference

manage landscape cover; instead, we require the user to manually identify each gardening zone type in the prototype. Once these areas have been indicated, the application manager can send the request to the landscape database and process the required calculations.

Potential rainwater collection to reduce the need for potable water for irrigation purposes is calculated by using the Rational Method (2012). This is a method for predicting storm water runoff when a high accuracy runoff rate is not essential. This is currently user-specified—that is, surface types are manually defined. The current version of Revit does not support surface type objects, nor provide potential zoning capability. Area can be retrieved directly from the Revit document. Related coefficients from the runoff database are used to determine the comparison rate from a base case to the design case.

## Water Efficiency

Table 6 gives a summary of the credits achieved.

In the case of water efficiency credit calculations, there is a need for information that is normally not found (even by default) in a building information model. These include properties such as flow rates; use numbers for plumbing fixtures, and plant specific information such as irrigation needs. Other information, for example, rainfall quantities, water harvesting systems, water treatment and storage systems can be supplemented from external sources. Although some of this information does not fall directly within the purview of the user, these are factors that have to be accounted for.

In this regard, it is interesting to note that, in practice, most LEED certified projects achieve water related credits as a strategy for attaining a minimum level of accreditation. For example, from a sample of LEED 2.1 Silver certified buildings in Pennsylvania, 88% of the buildings achieved credits for water use reduction, and 56% of the same set achieved 4 out of 5 possible credits. (USGBC 2011), however, this particular project did not go for the water credits due to high cost of efficient water fixtures at that time. For testing the prototype we added fixtures with required attributes to the model, and were able to automate evaluation of four water efficiency credits by combining information from the BIM.

## Energy and Atmosphere

The credits evaluated in the Energy and Atmosphere category mostly require data supplied manually by the user and from (essentially, third party) performance simulation results. Most of the credits in the energy and atmosphere category belong to the third type of assessment performed by the prototype. This type of assessment uses information from the model, external databases and simulation results, which are formatted and stored in order to evaluate according to LEED requirements. This test case achieved 30% energy use reduction, which is equivalent to 5 credits. The prototype is able to automate the evaluation of seven out of the nine credits achieved by the test case.

**TABLE 6.** Results achieved using the prototype in the Water Efficiency. (Achieved and Prototype)

Certified Case Practice	General Prototype	LEED Category <i>Water Efficiency</i>	Points
0	4		5
		Water Efficient Landscaping:	
0	1	▪ Reduce by 50%	1
0	1	▪ No Potable Use or No Irrigation	1
0	0	Innovative Wastewater Technologies	1
		Water Use Reduction:	
0	1	▪ 20% Reduction	1
0	1	▪ 30% Reduction	1

	Requires extensions to existing BIM entities and external data
	Requires new BIM elements and external data

### Indoor Air Quality

A large number of the credits in this category require user input mainly to acknowledge that certain procedures have been taken such as carbon dioxide monitoring, construction indoor air quality management plan, and indoor chemical source control etc. We have categorized these credits as manual and are working on a process to appropriately handle them. Credits that can be computed are those that can be queried from material characteristics that have been augmented such as the amount of Volatile Organic Compounds (VOC) present in adhesives, paints and carpets. As a majority of the credits in this category require manual input, few could be automated at this juncture.

### Materials and Resources

The Material and Resources category of LEED employs the most number of existing Revit objects. It also requires the most number of attribute extensions. The following parameters have to be extended in this category are ‘reused’, ‘recycled’ including ‘post-consumer’ and ‘pre-consumer’, ‘local material’ and ‘manufacturer’, ‘distance of manufacture’, ‘distance of harvest’, ‘rapidly renewable’, and ‘certified wood’. These parameters have to be added to the whole set of materials used for assessment. In Revit materials have default attributes as existing and new. Walls have attributes to whether they are structural or interior. For evaluating for certified wood we needed to add that particular attribute to any use of wooden elements. In this category, the case study achieved six credits; our prototype automated four out of those six credits. Table 7 gives a summary of the credits achieved.

**TABLE 7.** Results achieved using the prototype in the Materials and Resources. (Achieved and Prototype)

Certified Case Practice	General Prototype	LEED Category <i>Material and Resources</i>	Points
<b>7</b>	<b>4</b>		<b>13</b>
Y	0	Storage & Collection of Recyclables	Required
		Building Reuse:	
1	1	▪ Maintain 75% of Existing Shell	1
1	1	▪ Maintain 100% of Shell	1
0	1	▪ Maintain 100% Shell & 50% Non-Shell	1
		Construction Waste Management:	
1	0	▪ Divert 50%	1
1	0	▪ Divert 75%	1
		Resource Reuse:	
1	0	▪ Specify 5%	1
...	...	.....	
1	1	Certified Wood	1

	Achieved by only using existing BIM elements
	Requires extensions to existing BIM entities and external data

## **Summary**

Of the total 36 credits achieved for the test case using the traditional process, one third of those credits can be automated by the prototype from the following kinds of information: directly from the model, augmented parameters of existing Revit objects, external databases and simulation results, together with user input of options for certain credits. If the full extent of missing information is supplied, the prototype could evaluate potentially 70% of the credits. The remaining 30% of the credits relate to post design data, for example, data relating to commissioning, construction or monitoring.

In summary, the elements (and families) in Revit Architecture 2010 accommodate 11% of LEED NC 2.2 requirements. By extending existing Revit elements/families, an additional 56% of LEED requirements can be accommodated. For the remaining 33% of the credit requirements, the building information model has to be supplemented by external databases, references or information. We expect a similar finding for evaluating LEED 2009 requirements.

## **RESULTS AND SUMMARY FOR PROTOTYPE 2**

Analysis of filling LEED NC 2.1 templates shows that, on average, 45% of the fill data is retrieved from the COBie model without augmentation, and the remaining 55% is retrieved from data that is added to COBie. Of the latter, 35% can be identified as attributes of the building elements. This includes data that has to be post processed from simulation results, for example, for energy and lighting. The remaining 20% mainly pertain to queries related to support documents that are required for submission.

One of the challenges of developing a framework for sustainability relates to its usability over evolving rating guidelines. Table 8 gives a comparison of data points required to fill LEED NC 2.1 and LEED 2009 for the Sustainable Site category. This same trend of requiring more detailed data is likewise seen in the other categories. The analysis on the data required for creating submission ready documents is based on the COBie model, current BIM to COBie translator, LEED NC 2.1 template requirements and information that was available from the case study. The analysis is subject to change with any new sustainable building rating system, for example, updating to LEED 2009 requires larger amounts of data as the submission templates are longer and require more detailed information from the model. Templates for LEED 2.1 SS 2 and LEED2009 SS 2 for the same case study are illustrated in Figure 16 for comparison. It should be noted that only a part of the LEED2009 SS 2 template is shown. As seen in the figure basic information such as the building area, property area, are required by both rating systems in order to explicitly show density calculations. Both require scaled site plans and other documents to be uploaded. However, the LEED2009 SS 2 template requires much more information to fill the template. The comparison of the two versions of LEED templates helps us to formulate the information requirements as rating systems evolve. It is important to our study and results as it allows us to demonstrate the flexibility and adaptability of the information structure and process for assessments.

## **CONCLUSION**

We have demonstrated an approach of using sustainability information to address some of the known factors by providing informed choices towards sustainable design within a software-based design environment. Two prototypes are described.

**FIGURE 16.** Templates for (left) LEED2.1 SS 2 (right) LEED2009 SS 2.

### SS Credit 2: Development Density

I, (Architect, Civil Engineer or Responsible party), Harriet Shupp, declare that the project increases localized density to conform to existing or desired density goals by utilizing a site that is located within an existing minimum development density of 60,000 square feet per acre.

Project Density		Density Radius		
Building Gross Square Footage (ft2)	Property Area (acres)	Density (ft2/acre)	Property Area (acres)	Radius (ft)
9,100	0.44	20454.545	0.44	415.329

Density Boundary		Gross Square Footage (ft2)	Property Area (acres)
BuildingA		55000	0.39
BuildingB		87500	1.033
BuildingC		157000	0.218
BuildingD		27560	0.298
BuildingE		45000	0.735
BuildingF		88,000	0.584
BuildingG		8000	0.242
BuildingH		33000	0.275
BuildingI		45000	0.574
BuildingJ		30,555	0.26
BuildingK		40,340	0.207
BuildingL		25,000	0.987
BuildingM		12000	0.413
BuildingN		12,000	0.275
BuildingO		12000	0.207
BuildingP		23000	0.23
Building Gross Square Footage		558955.000	
Total Property Area			6.928
Average Density			80680.572

I have also provided the following supplementary information to support the declaration:

The plan

The location highlighted on Site Plan. Includes density radius line.

Graphic scale provided on Site Plan

SS Cr2 (1 point): Project and surrounding area densities >= 60,000 sq ft per acre

Points Documented

Name: Harriet Shupp  
Organization: Engineering

### LEED 2009 for New Construction and Major Renovation

#### SS Credit 2: DEVELOPMENT DENSITY AND COMMUNITY CONNECTIVITY

**ALL OPTIONS**

Option 1. Development Density. The project site is in a community with a minimum density of 60,000 sf/acre net. Note: Select this path to take advantage of the established path for exemplary performance

Option 2. Community Connectivity. The project is within 7 mile of a residential zone or neighborhood with an average density of 10 units per acre net, is within 7 mile of at least 10 basic services, and has pedestrian access between the building and the services.

**DEVELOPMENT DENSITY**

An area plan or URL of an online map showing the project site, surrounding areas, development density radius, property identifiers and scale is required.

Select one of the following:

An area plan will be used to satisfy this requirement.

A URL of an online map will be used to satisfy this requirement.

Upload SS2-1. Provide an area plan which includes the development density radius, property identifiers and a scale. Note: For projects pursuing Exemplary Performance Path 2, provide an area plan which includes both density radii measures and distinguishes the properties within each radius with clear property identifiers

Table SS2-1. Development Density

Property Identifier	Building Square Footage	Site Area (sf)	Site Area (acres)
BuildingA	55000.00	16988	0.39
BuildingB	87500.00	45000	1.033
BuildingC	15000.00	9500	0.218
BuildingD	27560.00	13000	0.298
BuildingE	45000.00	32000	0.735
BuildingF	88000.00	25450	0.584
BuildingG	8000.00	10560	0.242
BuildingH	33000.00	12000	0.275
BuildingI	45000.00	25000	0.574
BuildingJ	30555.00	11325	0.26
BuildingK	40340.00	9000	0.207
BuildingL	25000.00	43000	0.987
BuildingM	12000.00	18000	0.413
BuildingN	12000.00	12000	0.275
BuildingO	12000.00	9000	0.207
BuildingP	23000.00	10000	0.23
Total gross building square footage (sf)		558955.000	
Total site area (acres)			6.928
Project development density (sf/acre)			20454.545
Average property density within density boundary (sf/acre)			80680.572
Density radius (linear feet)			415.329

Enter the project building data in the first row and add additional properties in subsequent rows to determine the average property density within the density boundary. Do not include physical education spaces that are part of the project site in "Site Area" cell of "Project building(s)" row below.

The first prototype integrates data requirements from rating systems requirement with data from a building information model, although the model had to be augmented with additional data. The focus of the prototype development originally was on providing feedback to users while working with commercial BIM software, and in identifying gaps in the BIM model rather than filling these gaps in the software. A user can work on the model, export the database and use the prototype. LEED rules are an integral part of the assessment engine; any change in the LEED rules had to be updated internally.

The second prototype focuses more on the functional database that enables LEED rules to be explicitly translated into a computable form, i.e. it can be easily updated as a module to accommodate rule changes without affecting the main parser. By following some instructions a user could translate LEED requirements into simple forms of addition, subtraction, division and multiplication and value comparison for assessing different credits. We assume that the model is sufficiently complete for assessment; if there is not enough information the templates remain empty. Updates can be accommodated by mapping changes in credit requirements and elements required for evaluation. Changes are updated in the LEED database and subsequently in the framework database. The process is presently performed manually. As for



**TABLE 8.** Comparison of LEED 2.1 and LEED 2009 data requirements for templates

Credit: Sustainable Site	Data Points		%Change
	LEED 2.1	LEED 2009	
SSp1	12	15	25.0
SS 1	12	11	-8.3
SS 2	20	29	45.0
SS 3	12	9	-25.0
SS 4.1	18	31	72.2
SS 4.2	15	33	120.0
SS 4.3	16	61	281.3
SS 4.4	18	48	166.7
SS 5.1	11	31	181.8
SS 5.2	11	32	190.9
SS 6.1	21	23	9.5
SS 6.2	11	19	72.7
SS 7.1	13	37	184.6
SS 7.2	13	40	207.7
SS 8	10	50	400.0

multiple rating systems applicability, the framework provides a general process for storing, supplementing and augmenting building information, mapping a wide range of elements required by a chosen rating system, and creating queries to assess the present information.

The research described here is work in progress and is part of work that looks at refining workflows for aggregating, processing and managing relevant sustainability information. Related to this is automated model checking for default information along user input. Creating a formalized representation of rating system informational requirements is a task for the future.

## ACKNOWLEDGEMENTS

We are indebted to Professor David A. Dzombak of the Department of Civil and Environmental Engineering for providing us with details of the Rational Method for calculating potential rainwater collection.

The work done for this project, integrating building information models and rating systems to create a sustainable BIM was funded by Autodesk®, which aims to bringing sustainability principles closer to design. We are indebted for the invaluable support and feedback from Phil Bernstein, Erin R. Hoffer and Jack Gray.

Research done for the second prototype, Automated LEED datasheets from lightweight IFC models was funded by US Army Corps Construction Engineering Research Laboratory (CERL-ERDC), which aims at integrating building information with sustainability assessments using COBie as an intermediary platform. However, any opinions, findings, conclusions or recommendations presented in here are those of the authors and do not necessarily reflect the views of either Autodesk® or CERL-ERDC.

## REFERENCES

- AlWaer H, Sibley M and Lewis J (2008) Different Stakeholder Perceptions of Sustainability Assessment, *Architectural Science Review*, 51 (1), 48-59.
- Barnes S and Castro-Lacouture D (2009) BIM-Enabled Integrated Optimization Tool for LEED Decisions, *Proceedings of the 2009 ASCE International Workshop on Computing in Civil Engineering*, Austin, TX, 258-268.
- Biswas T, Wang TH and Krishnamurti R (2012) Data Sharing for Sustainable Assessments: Using Functional Databases for Interoperating Multiple Building Information Structures, *CAADRIA 2012*, Chennai, accepted.
- Bunz KR, Henze GP and Tiller DK (2006) Survey of Sustainable Building Design Practices in North America, Europe and Asia, *Journal of Architectural Engineering*, 12 (1), 33-62.
- Building Research Establishment Environmental Assessment Method (BREEAM) (2012) <http://www.breeam.org/> (last accessed February 2012).
- Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) (2012) <http://www.ibec.or.jp/CASBEE/english/> (last accessed February 2012).
- Cole RJ (1999) Building Environmental Assessment Methods: Clarifying Intentions, *Building Research and Information*, 27(4), 230-246.
- Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) (2012) [http://www.dgnb.de/\\_en/certification-system/index.php](http://www.dgnb.de/_en/certification-system/index.php) (last accessed February 2012).
- East WE (2012) Construction Operations Building Information Exchange (COBie) <http://www.wbdg.org/resources/cobie.php> (last accessed December 2011).
- Eastman C, Teicholz P, Sacks R and Liston K (2008) *BIM Handbook A Guide to Building Information Modeling*, John Wiley & Sons, Hoboken, NJ.
- Fowler KM and Rauch EM (2006) Sustainable Building Rating Systems Summary, Technical Report PNNL-15858, Pacific Northwest National Laboratory, [www.wbdg.org/ccb/GSAMAN/sustainable\\_bldg\\_rating\\_systems.pdf](http://www.wbdg.org/ccb/GSAMAN/sustainable_bldg_rating_systems.pdf) (last accessed February 2012).
- Gething B and Bordass B (2006) Rapid Assessment Checklist for Sustainable Buildings, *Building Research and Information*, 34(4), 416-126.
- Geilingh W (1988) General AEC Reference Model (GARM) an Aid for the Integration of Application Specific Product Definition Models, *Digital library of construction informatics and information technology in civil engineering and construction*, [http://itc.scix.net/cgi-bin/works/Show?\\_id=w78-1988-165](http://itc.scix.net/cgi-bin/works/Show?_id=w78-1988-165) (last accessed February 2012).
- Gissen D (2003) *Big and Green Toward Sustainable Architecture in The 21st Century*, Princeton Architectural Press, New York, NY.
- Glaser BG and Strauss AL (1967) *The Discovery of Grounded Theory: Strategies for Qualitative Research*, Aldine Publishers, Chicago, IL.
- Keysar E and Pearce AR (2007) Decision Support Tools for Green Building: Facilitating Selection Among New Adopters on Public Sector Projects, *Journal of Green Building*, 2 (3), 153-171.
- Kotnik T (2010) Digital Architectural Design as Exploration of Computable Functions, *International Journal of Architectural Computing*, 8 (1), 1-16.
- Krishnamurti R, Biswas T and Wang TH (2010) Soft Tools for Sustainability, In (Eds P Russell and O Schoch) *From Napkin to BIM*, to appear.
- Krygiel E, and Bradley N (2008) *Green BIM: Successful Sustainable Design with Building Information Modeling*, Wiley Publishing Inc., Indianapolis, IN.
- Nguyen TH, Shehab T, and Gao Z (2010) Evaluating Sustainability of Architectural Designs Using Building Information Modeling, *The Open Construction and Building Technology Journal*, 4, 1-8.
- Parr A and Zartesky M (2010) *New Directions in Sustainable Architecture*, Routledge, New York, NY.
- Rational Method (2010) <http://water.me.vccs.edu/math/rational.htm> (last accessed February 2012).
- Smith DK and Edgar A (2008) Building Information Modeling (BIM), <http://www.wbdg.org/bim/bim.php> (last accessed February 2012).
- Todd AJ and Fowler KM (2010) Measuring Performance of Sustainable Buildings, <http://www.wbdg.org/resources/measperfsubstbldgs.php> (last accessed February 2012).
- Trusty WB (2008) *Introducing an Assessment Tool Classification System*, <http://www.athenasmi.ca/publications/docs/AssessTypologyTool.pdf> (last accessed December 2011).
- US Department of Energy: Energy Efficiency & Renewable Energy (EERE) (2011) Building Energy Software Tools Directory, [http://apps1.eere.energy.gov/buildings/tools\\_directory/](http://apps1.eere.energy.gov/buildings/tools_directory/) (last accessed February 2012).

- United States Green Building Council (USGBC) (2006) *New Construction and Major Renovation Reference Guide*, Washington, DC.
- United States Green Building Council (USGBC) (2010) <http://www.usgbc.org/Docs/News/LEED%20Automation.pdf> (last accessed December 2011).
- United States Green Building Council (USGBC) (2011) LEED Projects Directory, <http://www.usgbc.org/LEED/Project/CertifiedProjectList.aspx?> (last accessed December 2011).
- United State Green Building Council (USGBC) (2011) Fact Sheets and Policy Briefs, <http://www.usgbc.org/DisplayPage.aspx?CMSPageID=2501> (last accessed August 2012).
- Williams LC (2010) The Pragmatic Approach to Green Design Achieving LEED Certification from an Architects Perspective, *Journal of Green Building*, 5 (1), 3-18.
- Wu W and Issa RRA (2010) Feasibility of integrating building information modeling and LEED certification process, In (Ed W Tizani) *Proceedings from the International Conference on Computing in Civil and Building Engineering*, Nottingham University Press.