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LIFECYCLE EVALUATION OF BUILDING SUSTAINABILITY USING BIM AND RTLS

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ABSTRACT

The purpose of this research is to provide a lifecycle building sustainability evaluation method to guide different stakeholders in how to apply sustainable practices and maintain the expected sustainability. Building Information Modeling (BIM) is selected to be a platform to integrate all the information to improve interoperability. Green standards are embedded in the BIM model and a rule-based system is developed to automatically evaluate the design and the building performance. Data are collected by using a Real-Time Location System (RTLS) and are used to update the BIM model. The as-built model is checked to see if it matches the sustainability aspects regarding the construction processes. During operation, energy consumption data are collected and analyzed. The performance of the building is checked to see if the designed features reach the sustainability goals. By integrating the BIM, RTLS, and other information, a prototype system of lifecycle sustainability evaluation is developed and tested.

1 INTRODUCTION

According to United Nations Environment Program, more than 40 percent of global energy is consumed by buildings, and one third of global greenhouse gas is produced by buildings (UNEP 2009). Sustainability issues are the major concerns for building stakeholders to find a trade-off between environmental and financial aspects of designing a building. Not only from the construction stage, but also from the operation stage, the energy consumption of buildings has the largest environment impact in the life cycle of a building (Khasreen et al. 2009). To provide a principal for sustainability concern, several green building standards, certifications, and rating systems were publicized in the last two decades. The first green building rating system in the U.K., Building Research Establishment's Environmental Assessment Method (BREEAM), was created in the 1990's. Later in 2000, Leadership in Energy and Environmental Design (LEED) rating system was released by the United State Green Building Council (USGBC). Apart from LEED, Green Building Initiative (GBI) finalized an agreement to introduce the Green Globes environmental assessment into the U.S. market in 2004 as an alternative to LEED. Additional rating systems have been developed which were based on those previous standards and then tailored to their individual national requirements.

Although these standards give a clear guide on how to meet the requirements of green buildings, the designers often encounter the challenges of limited time and the complexity to follow exactly all the detailed rules specified in the standards. Especially when the project is large and complex, it is inevitable to omit several rules and it is difficult for designers to select the most favorable design just based on

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experience, because the onerous process to weight different requirements and assessing building sustainable performance is both challenging and complex (Iwaro et al., 2014). Moreover, little consideration in terms of sustainability is taken into account during the construction process and possible consequences are excessive waste produced and environmental pollution. The sustainable construction aims for better management of resources and reducing the impact on the surrounding environment (Wang et al. 2014). Moreover, the continuous cooperation of stakeholders is undermined. A lack of long-term sustainable performance monitoring complied with designed aspects leads to not truly sustainable and environmental-friendly buildings. The absence of sustainable sense in the operation stage can be substantiated by the fact that the number of certifications for the design stage is more than ten times that for the operation stage (Li et al. 2013). Those above-mentioned factors impede the true realization of sustainable buildings.

To facilitate the wide spread of sustainable buildings more effectively, professionals in Architecture, Engineering and Construction industry (AEC) have introduced Life Cycle Analysis (LCA) and Building Information Modelling (BIM) into sustainable buildings (Jrade and Jalaer 2013). LCA is a systematic method to assess the impact of buildings on the environment from multiple perspectives, namely design, construction, operation and demolition. LCA can also be applied to one specific aspect of building, for example construction materials, because construction activities are the largest consumers of processed and raw materials; thus material selection significantly determines the environmental impact. During the design stage, the initial embodied energy of the materials is one important criterion to select materials because high embodied energy is associated with high levels of greenhouse gas emission. In addition, the material should be able to provide occupants with comfort and need to have low maintenance requirements during operation phase (Bribian et al. 2011).

BIM strengthens the collaboration among different stakeholders and aims for an information-rich database, which facilitates assessment of sustainability of building more accurately from life cycle perspective. BIM covers not only geometry information of objects, but also other specific attributes of objects for example material content and thermal conductivity. BIM is transforming from a simple information storage to a platform which can perform different kinds of analyses based on these raw data (Motawa and Carter 2013).

In the present paper, a lifecycle assessment on the sustainability of buildings is proposed, building aspects related to sustainability design, such as the selection of reusable material, and a long-term continuous performance monitoring, e.g. electricity and water consumption, and spatial analysis are integrated with BIM. First of all, building aspects that cannot be parameterized will be extracted and assessed by using predefined rules. The more aspects of building are considered and assessed in this system, the more convincing the overall sustainability assessment result will be. In addition, this categorization helps the designers to pay more attention to those requirements which cannot be translated to digital expression. Second, the sustainable performance will be monitored during the whole life-cycle. The assessment includes annual power and water consumption and survey on occupants. The gathered information can be recorded to assess life-cycle sustainability and to guide future sustainable design. In some situations, high energy consumption may be due to the behavior of occupants rather than the building design, and the results collected from continuous assessments will help people find the true cause of high energy consumption.

2 LITERATURE REVIEW

2.1 Green Building Standards in China

The concept of energy-saving buildings was initiated in China in the 1980's, and then a large amount of research was put forward in the last decades along with the acceleration of urbanization. The central government has emphasized the application of green buildings in the five-year plans to deal with the public claims of environmental pollution (Kong et al. 2012). The Chinese national green building standards - Evaluation Standard for Green Building (ESGB) was enacted in 2006. ESGB supports the

Ministry of Housing and Urban-Rural Development (MOHURD) to certify green buildings. Once the building is certified, it will be issued a Green Building Label (GBL). The Center of Science and Technology of Construction of MOHURD and the Chinese Society for Urban Studies (CSUS) are two main evaluation agencies, which can issue one-star, two-star and three-star green building labels with the three-star being the highest level. At the same time, about 30 local authorities became also entitled to certified one-star and two-star green buildings by June 2012 (Ye et al. 2013). GBL can be applied in either the design phase (Green Building Design Label, GBDL) or the operation phase, which is similar to other green building standards. The examination of GBDL is mainly based on detailed drawings, and the operation phase evaluation can be conducted after one-year service or longer. The evaluation is also separated for residential projects and public projects, because the provisions differ according to the category of buildings. However, the number of categories of buildings in the ESGB standard is less when compared to LEED or BREEAM, which have about 10 versions for different buildings. In ESGB, six aspects of projects are assessed, namely land efficiency and ambient environment, energy efficiency and utilization, water efficiency and utilization, material efficiency and utilization, indoor environmental quality, and operation management (Zhu et al. 2010). Since 2008, the annual number of projects issued a Green Building Label has started to increase significantly. By 2011, at least 76 cities had GBL projects. However, the distribution around the country is uneven. Most of the GBL projects are in the east of China, where many large cities are located. Shanghai has 47 GBL projects, which is the highest number in one city. Although the number of buildings issued a GBL is increasing sharply, the influence of GBL in China is still less than the influence of other standards, like LEED in the USA and BREEAM in the UK, due to its late starting point (Zuo and Zhao 2014).

Among different green building standards, Leadership in Energy and Environmental Design (LEED) is widely used across the world. The LEED rating system is a voluntary and third-party certification program initiated by the USA Green Building Council. Although LEED is initiated from the USA, it has established a global reputation as a benchmark of green buildings. In Asia, more than 500 projects have been certified over the past five years, and most of these projects are from China and India (Thilakaratne and Lew 2011). It has been observed that many building developers in China favor foreign green building standards to attract international investors, and LEED becomes their first choice. LEED has certified projects in 24 different countries, and there were 172 certified projects in China by March 2012 (Chen and Lee 2013).

2.2 Building Information Modelling (BIM) and Sustainability Analysis

Building Information Modeling (BIM) is a new approach to design, construction, and facilities management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in a digital format (Eastman et al. 2011). Kryegiel and Nies (2008) indicated that BIM can be applied in sustainability analysis widely while considering for example building orientation, building envelope, and construction materials. With the introduction of BIM, different attributes of the building envelopes can be recorded in the digital database, for instance carbon dioxide emission, which facilitates the automatic sustainability assessments of buildings. Chen and Hsieh (2013) developed a BIM-assisted rule-based approach to automatically check greenhouse gas emission of buildings. The carbon dioxide emission was calculated from the building and the area covered by plants; and then the result would be checked with relevant rules. However, most of these applications are limited to the design stage.

Using BIM is also changing the manner of constructing buildings in the construction industry. The relationship of space and time can be accurately described in a systematic way in 4D modeling. Several approaches have been proposed analyze spatial conflicts and to improve safety and efficiency on site based on the spatiotemporal information provided by BIM (Zhang et al. 2012). Kiviniemi et al. (2011) have used BIM as a 4D safety planning tool, in which the researchers have indicated that BIM technology can present a new way to solve site safety problems. Moreover, as indicated by Motamedi et al. (2013), a more efficient facilities management system can be built by sharing and exchanging distributed data based on the integration of Radio Frequency Identification (RFID) systems and BIM. Li et al. (2014) developed a BIM centered indoor localization algorithm to support building fire emergency response operations. They designed an environment-aware beacon deployment algorithm to support a sequence-based localization schema.

The authors of the present paper have been working on RFID Integrated BIM method for safety and facility management (Zhang et al. 2012; Zhang et al. 2013) and for improving productivity during construction (Hammad et al. 2012). The scope of the present study is to propose an approach for the lifecycle sustainability evaluation of buildings using BIM integrated with sensing systems. The objectives are: (1) to propose an approach for effective and integrated sustainability assessment following LEED standards based on a life-long monitoring; (2) to investigate different sustainable requirements during different phases of the building lifecycle and embed them into BIM models; and (3) to design an RTLS for data collection and to update the BIM model regarding to the dynamic construction situation and operation performance.

3 METHODOLOGY

3.1 Framework

Design, construction and operation are three different phases which need to be considered together when assessing the sustainability of the buildings according to LEED documents (Figure 1).

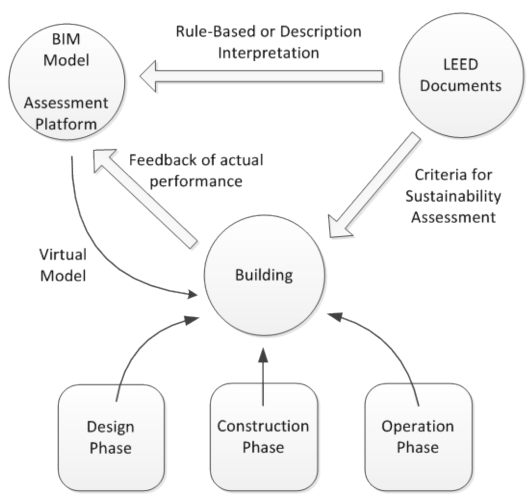


Figure 1: Framework of Rule-based Assessment of Building Sustainability in BIM

Starting from design, a rule-based system is proposed for checking building codes and providing instruction to sustainable design practice. LEED documents should be reviewed carefully and designers should reach preliminary agreements about sustainability with clients and report the expected sustainable performance. All the credits in LEED documents are divided into two sub-categories. Some credits can be explicitly expressed in parametric format in the model, while some credits rely on manual description and human judgments. For example, in SS Credit 7.2, solar reflectance index (SRI) of roof and area of this specific roof can be retrieved from element parametric representations; while in MR Credit 2 the percentage of construction and demolition debris that is redirected to manufacturing process needs to be determined by the user. If the credits can be related to one specific attribute in the model, the relationship between credits and the parametric values should be clearly defined. In addition, some credits might be related to attributes of different elements, and the combination effects should be considered. If the credits rely on manual description and judgments, a check system is used to ensure the design corresponds to

LEED documents. Rules are developed and categorized into groups. Embedding those parameters and rules in BIM can help in applying sustainable design practices and evaluating the design at the same time.

Next, in the construction phase, the project manager needs to check the feasibility of the buildings according to local resource availability and modify the initial design if necessary. If any recommendations are made, the change should be reflected in the model and the expected performance should be updated. The construction contractors also need to report their construction documents, namely construction method, construction schedule, and waste management plan. These construction documents will be used to assess the sustainability at the construction phase according to LEED standards. Recent studies have identified inefficiencies and waste in the construction phase due to the lack of proper integration of efforts between various stakeholders. Therefore, a Lean Construction (LC) approach can be applied using BIM as a core database for schedule, cost and other related information. Through early collaboration and the use of BIM technology, a more integrated, interactive, virtual approach to building design, construction and operation is emerging. An RTLS is designed in this research to collect data from tagged objects. This system is designed together with the structural, the MEP, and other main components from the planning and design phase. Radio Frequency Identification (RFID) can be used to monitor construction materials, pre-cast components, steel structure components, HVAC components, etc. to enable lean construction, and improve safety on construction site. The collected data will be used to update the BIM model so as to facilitate a second-round evaluation based on the current situation of the building.

Finally, in the operation phase, the information about the annual energy and water consumption should be collected, and surveys on occupants' behavior are also recommended to facilitate the assessment of user experience. For example, in IEQ Credit 7.2 a thermal comfort survey is taken within 6 to 18 months after occupancy to collect anonymous responses about the thermal comfort in the building. In addition, the actual performance of the building should be monitored and compared with the expected values. For example, space (area/room) defined in BIM model is associated with energy consumption information, which gives guidance to future spatial design work. The patterns of the energy consumption will be analyzed in terms of the spatial characteristics of rooms, areas, and zones. More analysis should be done to set a threshold for energy consumption, to shoot troubles, to schedule inspections, and to optimize maintenance resources.

3.2 Integration of LEED and BIM

3.2.1 Information required from BIM

Since the purpose of the present research is to automate the sustainability evaluation, information is expected to be retrieved from the BIM model as much as possible. Quantity take-off is one of the most useful information that can be easily retrieved from the BIM model. Several credit evaluations are based on cost, which requires a detailed analysis of quantities. For example, the intention of Material and Resources (MR) credit-3 is to encourage reuse of building materials, in order to reduce demands for virgin materials and reduce waste. The credit requires that the sum of reused materials accounts for at least 5 or 10 percent, based on cost, of the total value of materials. In this case, materials' cost can be calculated based on the quantities take-off from the model and the unit price that need to be input by the user. That requires a design for inputting more information during the design phase. Generally, the BIM model has not only geometric information of objects, but also other valuable information about the attributes of these objects, for example materials of objects and specific attributes for energy analyses usage. After a thorough review of the LEED document, the required information is summarized for each type of building components, such as Roof, Wall, Floor, etc. That extra information is required to be input by the user during the design phase. A hierarchy of element defined in BIM makes this process more efficient. The hierarchy of elements is normally *category*, *family*, and *type*. The *category* is well defined and built and cannot be changed, e.g., *wall* and *door*. The *family* is defined as a more specific version of objects in a particular category, e.g. *swing door* and *sliding door*. It includes *system family* and *component family* and both *families* can be modified or customized to fulfill different purposes. For example, in evaluating the Heat Island Effect of a roof, extra information such as Solar Reflectance Indexes (SRI) for roof elements should be defined during the design phase. The value of SRI should be input and stored in the customized *Roof Properties* for further evaluation, which is described in Section 4.1.

3.2.2 Rule-based Assessment

The core part of the evaluation system is based on all kinds of rules developed according to the LEED requirements. The three main items of the rule-based assessment are *Input*, *Analysis* and *Output*. First, inputs vary according to requirements of different credits. Some can be parameterized while some need the designer to choose the closest description. For example, MR Credit 3 describes the percentage of reusable material of the total value of materials of the project, based on cost. Theoretically, this information can be retrieved by either parameterized properties or manual description. If it is obtained from parameterized properties, the reusable material pertaining to an individual instance should be specified, and then the whole percentage can be calculated. Alternatively, the percentage of reusable materials in the whole project can be input directly by the user through the interface. The latter choice is preferable due to pragmatic considerations. To facilitate the assessment based on description, the designer needs to choose the closest description of the project, and if necessary, a hierarchical selection can be integrated into the interface to allow the designer to achieve better estimation. The *Input* not only includes the information of the building itself but also other external supplementary information, for example RSMEANS construction market unit price, because this external information is vital to calculate the percentages of different materials of the total value of materials, based on cost. A user interface should be designed to facilitate the input of other information. In the user interface, each LEED credit is listed explicitly and the user can select the one that he/she wants to examine. After the selection, all the parameterized properties and description options available to this credit will be shown in the interface. The user can modify the parameterized properties and update the model, and select the most suitable description option.

The *Analysis* part is to calculate the result based on the *Input* for each credit defined in LEED. Taking the same example of Hot Island Effect evaluation of a roof, there are three options to fulfill the requirements of this credit. The first option is that at least 75 percent of the roof surface should satisfy the requirement of solar reflectance index (SRI), according to Equation (1). The requirements of SRI also vary according to the slope of the roof. For low-sloped roof, namely the slope is less than 0.15, the required SRI value is 78. For steep-sloped roof, namely the slope is larger than 0.15, the required SRI value is 29. Alternatively, the credit can be earned when a vegetated roof covers at least half of roof area. The third option is a combination of the previous two conditions, according to Equation (2). In addition, if 100 percent of the roof area is made up of vegetated roof system, it may earn an Innovation in Design credit. Finally, the *Output* will show the credits this project can get and feedback about further improvements.

$$\frac{\textit{Area Roof Meeting Minimum SRI}}{\textit{Total Roof Area}} \times \frac{\textit{SRI of Installed Roof}}{\textit{Required SRI}} \geq \mathbf{75\%} \tag{1}$$

$$\frac{\textit{Area Roof Meeting Minimum SRI}}{0.75} + \frac{\textit{Area of Vegetated Roof}}{0.5} \geq \textit{Total Roof Area} \tag{2}$$

3.3 Integration of RTLS and BIM

As mentioned previously, space (area/room) defined in BIM model is associated with energy consumption information, which gives guidance to future spatial design work. The patterns of the energy consumption will be analyzed in terms of the spatial characteristics of rooms, areas, and zones. To facilitate a sustainable construction (e.g., a lean construction) and to build a spatial relationship between energy consumption and space design, an RTLS is designed to collect data and update the BIM model during construction and operation stages. During construction, work breakdown structure (WBS) is used to create the hierarchy of the tasks and subtasks of the construction project. Each WBS deliverable is associated with a reference object, which can be building components including Mechanical, Electrical and Plumbing (MEP) components, and temporary structures. RFID tags are attached to building components, facilities, and other objects that can be tracked. Data of RFID tags are collected using handheld/fixed receivers and then transferred wirelessly through GPRS to the office without interrupting the construction activities, considering the availability of other techniques, e.g., wifi may not be available on a construction site.

For prefabricated materials, e.g., steel elements, tags may be available before being transported to construction site. Usually, information saved in those RFID tags attached to components includes the material/component name, type, manufacturing date, transportation, and installation, etc. depending on the characteristics of the material/components. For those tags, information should be collected and tags should be registered in the BIM model immediately after the installation. After that, an updating of the tag network should be applied to reflect the changes. It is ideal to tag all the components to build a complete database; however, this will result in a huge number of tags in the building, and may increase the difficulty in managing scattered data in a centralized database. In order to have a cost-effective system, tags will be attached to components that have distinguished sustainability characteristics and cost-effectiveness should be taken into consideration. Therefore, a hierarchy is defined to build an effective network according to the required level of details. A three-level tag network is suggested in Zhang et al. (2013). Once installed, RFID tags are registered/represented in the BIM model. Location and other data stored in the tags are saved in the BIM database. An experimental investigation of the RFID integration can be found in Zhang et al. (2013).

4 IMPLEMENTATION

Autodesk Revit is selected in this research as a platform to develop the lifecycle evaluation system. A general user friendly interface is designed to facilitate the input process. The analysis is done based on information retrieved from the BIM model and additional data input by the user during different phases of the building lifecycle. An RFID system is used to collect real-time data, including location data and data saved in the tags, e.g., energy consumption, through the construction and the operation of the building.

4.1 Rule-based Analysis

Rules are developed for all the credits defined in LEED. Taking SS Credit 7.2 (Heat Island Effect -Roof) as an example, which puts forward requirements on the selection of the roof, in order to minimize the influence of heat island in the city. Two values are vital for calculating the result, which are the Solar Reflectance Index (SRI) and the percentage of vegetated roof (PVR). The input of those values by the user into customized properties is necessary at the beginning. However, considering the *roof* belongs to a *system family* which means it cannot be modified directly by the Family Editor, the extra properties can be added by "project parameters" function in Revit. In the interface of "project parameters" function, parameter type, parameter data and categories need to be defined (Figure 2(a)). There are two kinds of parameter types, namely *project parameter* and *shared parameter*. Project parameters are particular to the current project while shared parameters can be stored and shared with other projects. Shared parameters can also appear as tags on the drawings. However, project parameters are more flexible and shared parameters require careful data management. Under the parameter data section, the user needs to set a series of information about the parameter (e.g. name and discipline). It is also necessary to define the *property* as a type parameter or instance parameter.

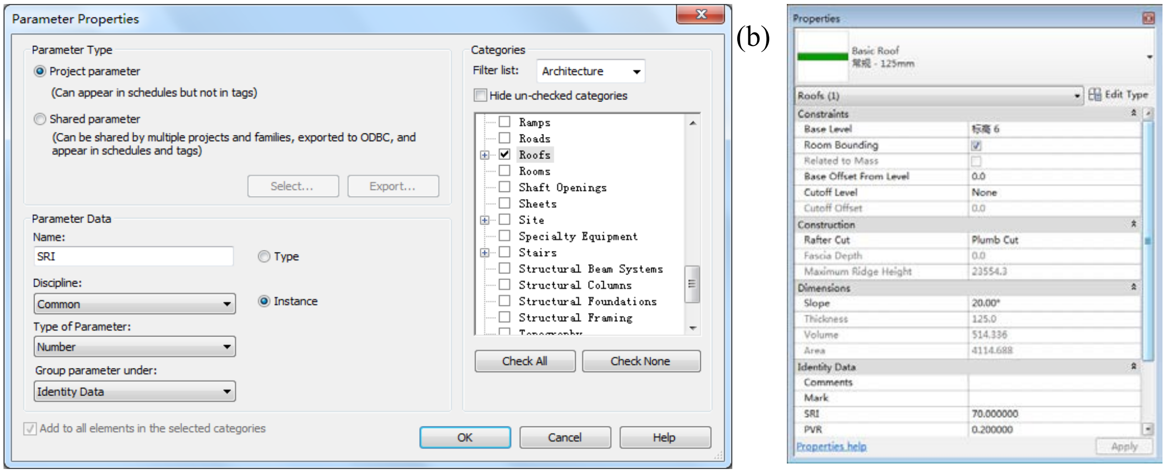


Figure 2**:** Customized Properties of Roof

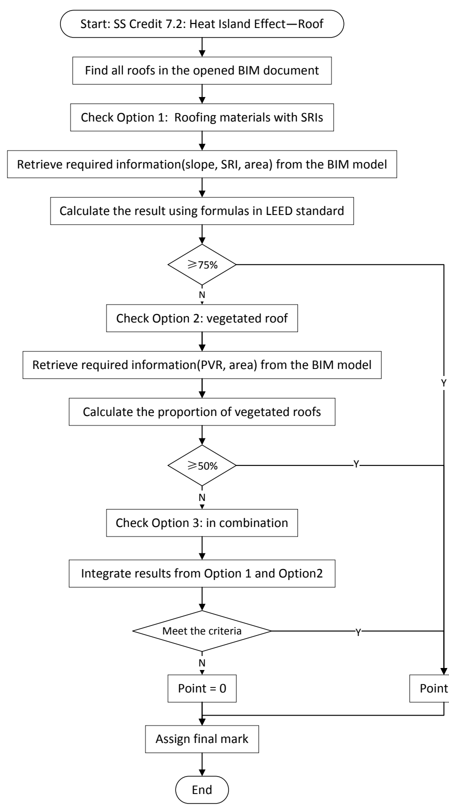


Figure 3: Flowchart of Heat Island Effect of Roof Design

A *Type parameter* defines the property of objects of the same type, for example the price of a double door 1800 mm wide and 2100 mm high. A *Instance parameter* defines the property of individual objects, for example the unique number of each door. The user needs to attribute the parameter to a specific category. For SS Credit 7.2, SRI and PVR are added to the identify data properties of a roof as *instance parameters* (Figure 2(b)). During the analysis, data stored in the *Properties* of the roof are retrieved, a flowchart is shown in Figure 3 to describe the steps of evaluating the roof performance using the three options. One point is assigned to the design if any of the options is fulfilled.

4.2 RFID Integration

RFID tags are registered/represented in the BIM as temporary or permanent objects depending on the requirements of construction and operation. Location information together with other data (energy consumption collected from other sensors) stored in the tags are read and saved in the BIM database for further analysis related with spatial aspects. For example, energy consumption for a specific area or room. In this way, energy consumption can be analyzed in a way that the spatial issues can be taken into account. A 2.4G Hz RFID system is selected to be tested in this research. Passive and active tags are both used to test the visibility and effectiveness. Plug-ins are developed to load data collected from the RFID tags into BIM and to create the corresponding tags in the model. Figure 4(a) shows the writing and reading data procedures. Figure 4(b) shows the user interface of data read/write through a fixed RFID reader. A new object *family* is created to represent tags in the BIM model as shown in Figure 4(c). Tag ID, Location, Reference object, Host, etc. are stored in the *Properties*. Those data can be updated automatically or modified manually. Each RFID read-and-write (RW) tag can store 4KB data, where information including the tag ID, reference objects, etc., can be written to the memory at any stage of the construction. That information will be read and saved to the *Properties* of each tag after the tag is detected on site. In addition, once the information in the *Properties* of each tag is updated, the same information can be written to the memory of the RFID tag as well. An experimental investigation of using FRID integrated BIM model for safety and facility management can be found in one of the authors' publication (Zhang et al., 2013), which shows the feasibility of integrating RTLS into BIM.

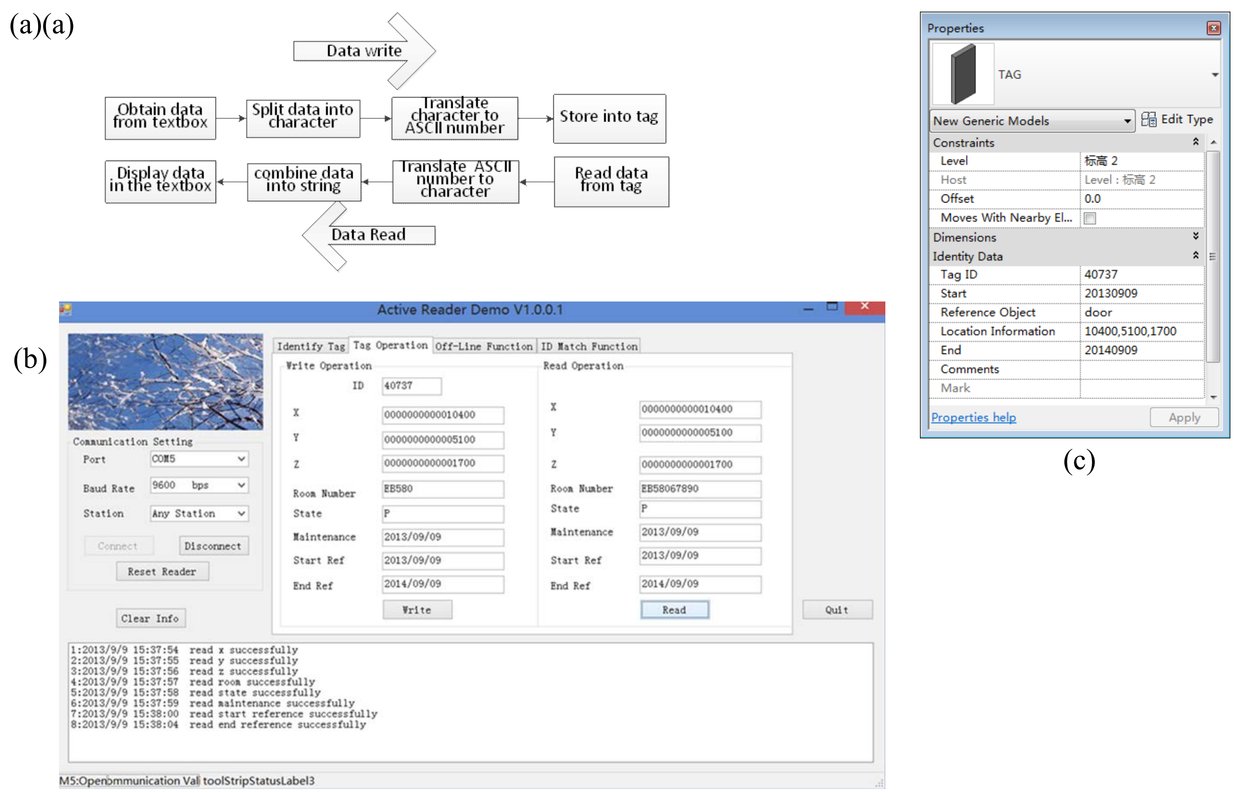
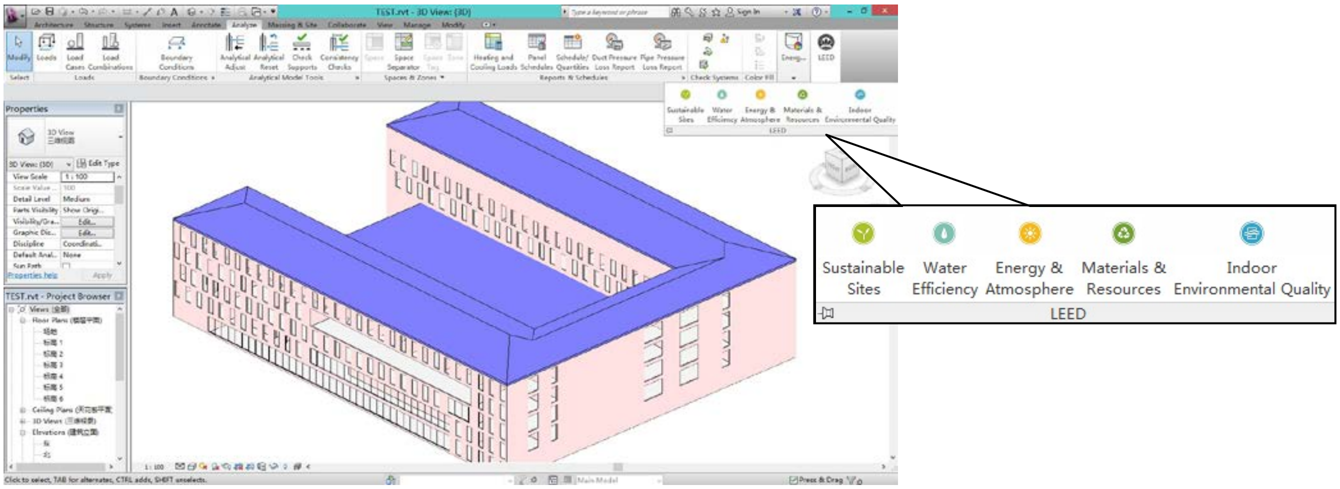


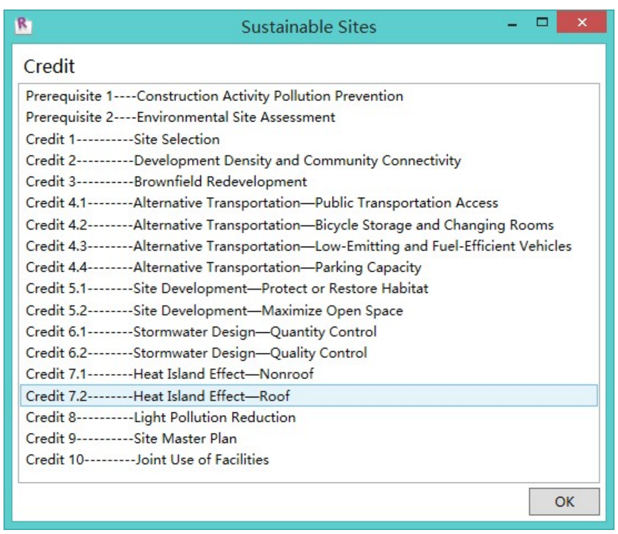
Figure 4: RFID Data Read/Write and Representation in Properties

5 CASE STUDY

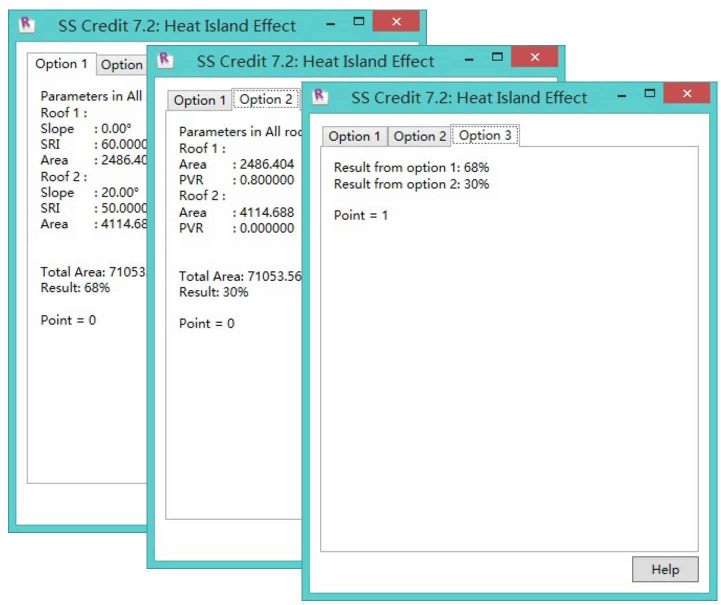
The project selected for the case study is the Engineering Building at Xi'an Jiaotong-Liverpool University. A BIM model was created by using Revit based on 2D AutoCAD drawings. It is a U-shape building with five floors. LEED 2009 for Schools New Construction and Major Renovations (2013) is integrated in the BIM model (Figure 5(a)). Figure 5(b) shows the user interface of Sustainable Sites credits. Figure 5(c) shows the three options of gaining credits for Roof design in terms of Heat Island Effect. Based on the description in Section 4.1, 1 credit is gained from the roof design.



(a)



(b)



(c)

Figure 5: Heat Island Effect Evaluation Result of Roof

Figure 6 shows an example of the RFID integration, where tags are attached to office doors for long-term data collection. A preliminary test was applied for reading data from tags, and the representing the tags and saving data stored in the tags into the BIM model. More details can be found in Zhang et al. (2013).

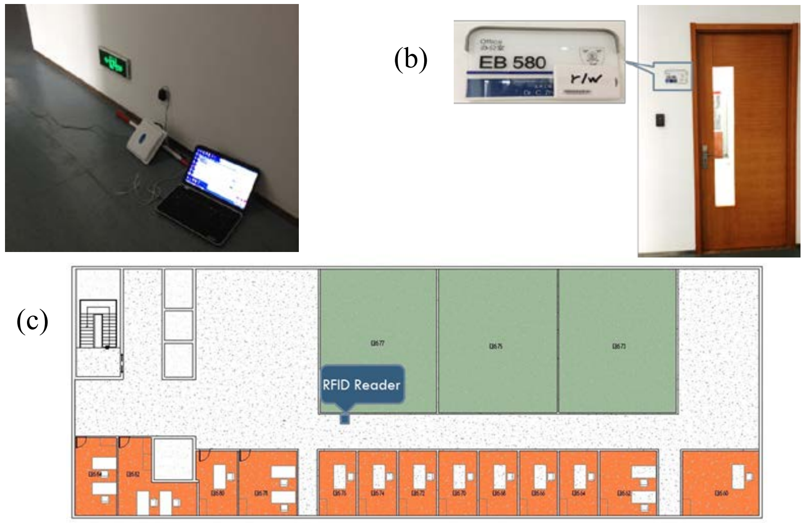


Figure 6: RFID Integration

6 CONCLUSIONS AND FUTURE WORK

This paper describes a building lifecycle sustainability evaluation system. LEED standards are embedded in the BIM model and automatic evaluation is done based on information either retrieved from the model or input by the user during different phases of the lifecycle. A rule-based system is developed to calculate the credits gained from the building design and the building performance. An RTLS is designed to collect data from the construction site and from operation situations. A prototype system is developed and a case study of a university campus in China is applied. Our future work focuses on data collection during the construction and operation phases so as to reflect an as-built situation of building sustainability.

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