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Modeling of the Sustainability Goal and Objective Setting Process in the Predesign Phase of Green Institutional Building Projects

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Abstract: The process of constructing a sustainable green building presents a number of challenges compared with regular buildings. Additional work and documentation is needed in every stage of the project life cycle for the sustainable building to reach its goal of being certified according to one of the available sustainability rating systems. One of the most important steps toward achieving that goal is the eco-charrette process that takes place during the predesign phase of the project. The importance of this step stems from the fact that it sets the sustainability goals and objectives for the entire project. This necessitates the creation of an effective decision support methodology that will support project stakeholders in setting the sustainability goals and objectives of the project before committing valuable time and budget resources to the eco-charrette process. Therefore, this paper presents the development of an agent-based model for simulating the interactions between project stakeholders in the sustainability goal and objective setting process of the project predesign phase. The proposed model was developed based on extensive interviews with industry professionals and project stakeholders, and was tested and validated using a case study of an institutional building project. Simulation results were shown to closely resemble the actual case studies evaluated and highlighted the sensitivity and relationships of building design parameters. **DOI:** 10.1061/(ASCE)AE.1943-5568.0000138. © *2013 American Society of Civil Engineers.*

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Introduction

The construction industry has been recognized worldwide as one of the contributors to the escalation or alleviation of the environmental challenges that are faced by our planet (EPA 2010). This has led to the development of organizations and policies that encourage environmentally conscious buildings and construction practices. There are many standards and frameworks that provide guidance for the construction of green buildings, including green-building rating systems (Gowri 2004). Green-building rating systems provide specifications and standards to achieve different levels of certification that represent how environmentally sustainable the constructed building is.

Project architects and engineers interact during the predesign phase to develop sufficient strategic information for the owner to determine the initial financial requirements and the ability to achieve the project objectives (Gibson et al. 1995). Typical predesign tasks include structured and unstructured meetings of major project stakeholders to strategically determine project goals, opportunities, priorities, and constraints (Parrish and Regnier 2013). In green-building projects, initial project stakeholders converge in a process called the eco-charrette during the predesign phase to agree on project sustainability goals, which is then translated into the desired certification level for the green building. The eco-charrette process involves three main building stakeholders: owner/client, designer/architect, and representative group of building users (Bayraktar and Owens 2010). During the eco-charrette process, these stakeholders make informed decisions about the targeted level of building sustainability certification considering the available predesign information. This available information usually includes building-site characteristics, applicability of various technologies to achieve the set objectives, and preliminary cost implications of these technologies. Following an initial assessment, alternatives and possible actions are proposed, discussed, and refined until the stakeholders agree upon an alternative. Finally, the chosen alternative is implemented. The whole process typically takes an immense amount of time and calculation, without having any optimal or efficient way for selecting the project sustainability goals and objectives (Bayraktar and Owens 2010). The current practical approach for this selection process includes intensive design meetings and charrettes to determine the possibility of pursuing a certification level of a sustainability rating system.

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Although a large number of previous studies have extensively investigated sustainable building design, there are limited studies that examine the interactions between stakeholders and how their interactions would impact the setting of a building project's sustainability objectives. Modeling stakeholders' interactions is critical because the green-building predesign phase is accomplished mainly through a set of collaborative meetings and charrettes, which cannot be modeled using traditional analytical techniques. This creates a need for understanding and evaluating the various stakeholders involved and their interactions in sustainable building projects. A particular focus on the predesign phase of the project life cycle is needed because of its strong influence on the downstream phases of the project.

Objective

This paper attempts to bridge the aforementioned research gap by developing a simulation model that encompasses the project's initial stakeholders and their interactions in the predesign phase of sustainable building projects. The proposed model is part of a bigger research project that attempts to develop an understanding of the impact of legislation and public policies on the adoption of sustainability in the construction industry. This model, as an individual tool, will help owners and developers in evaluating their projects based on a building sustainability rating system, namely, Leadership in Energy and Environmental Design (LEED) [U.S. Green Building Council (USGBC) 2013], to strategically determine the level of certification that can be achieved based on a number of preliminary inputs from stakeholders. Hence, the proposed model could be utilized in effectively setting the sustainability goals and objectives for the project. The proposed model would greatly help project owners in strategically determining the ability to pursue building sustainable design before committing time and financial resources in an intense predesign process. It should be noted that the proposed model does not substitute the human-based process or prohibit the opportunities of innovative design solutions. Rather, it is envisioned as an early decision-support tool to help project owners and investors in determining the feasibility of seeking target green-building certification without the need of allocating the time and financial resources to the regular design process.

The development of the proposed model will follow a seven-step methodology that spans over three main stages, as illustrated in Fig. 1: data collection, model formulation, and model implementation. The following sections discuss in detail each of the three development phases of the proposed model and the model performance utilizing a number of case studies and a sensitivity analysis.

Data Collection

The data required for the formulation and implementation of the proposed model was collected through an extensive review of current sustainable design practices and stakeholders' interviews.

Background Review

An extensive review was performed to investigate the current state of the art in three main areas related to the current study, namely:

1. Sustainable design practices in building projects;
2. Green-building rating systems; and
3. Previous studies of sustainable building design.

Building sustainability concepts in the United States originated in the 1970s after recognizing the need for energy efficient and environmentally friendly constructed facilities (Yudelson 2006). Sustainable building design can be defined as the process of creating the technical description of a new building that has minimum life-cycle impacts. This process usually includes three main phases: the predesign phase, which defines the technical requirements and sustainability goals of the proposed building; the design phase, which creates the detailed plans and specifications; and the preconstruction phase, which develops construction plans for the activities and resources required to make the design a physical reality (Yudelson 2006).

This study focuses on the predesign phase, which significantly influences the final design of the building and is performed in the absence of downstream detailed design information. The sustainability goals and objectives of the project are discussed early in the predesign phase during the eco-charrette meetings in which architects, engineers, and owner representatives come together to discuss the sustainable objectives the building would achieve. During this process, alternatives are examined and discussed with the potential end users and owner representatives to set the final objectives for the sustainable building (Yudelson 2006). The amount of information available for this sustainability goal and objective setting process during the predesign phase is minimal compared with other phases.

Green-building rating systems are utilized by designers to go beyond the basic code requirements to improve the overall building performance and to reduce its environmental impacts. Some of the most cited and used rating systems include the following: Building Research Establishment Environmental Assessment Method (BREEAM) (Roderick et al. 2009), LEED (Bayraktar and Owens 2010), Green Globes (Smith et al. 2006), Green Star (Roderick et al. 2009), and Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) (Gowri 2004; Fowler and Rauch 2006). All these rating systems differ in their terminology, structure, performance assessment methods, and documentation requirements for certification. However, the major focus of these rating systems revolves around five basic and important impact categories: site, water, energy, materials, and indoor environment. A previous study (Xiaoping et al. 2009) identified LEED as the most flexible, easy to implement, and widely adopted rating system. Therefore, the current study will adopt LEED in the development of its proposed model.

LEED is a voluntary standard and verification of green buildings that was developed by the USGBC in 1998. Since then, it has gone through revisions and refinement to include different project types,

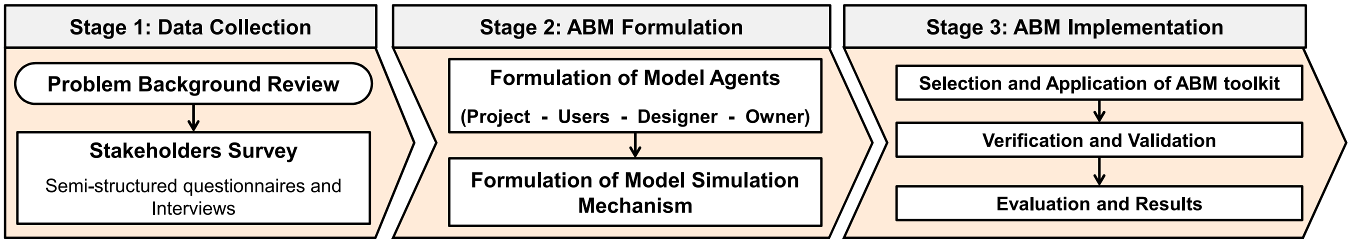

Fig. 1. Proposed model development methodology

such as new construction, existing construction, commercial buildings, homes, schools, healthcare, and retail. LEED provides guidelines and specifications for building construction to achieve its sustainability goals and objectives. LEED is similar to a checklist of credits that can be achieved in five major categories: indoor environment, energy and atmosphere, water, materials, and site. Bonus credits can be achieved in other categories such as innovation in design, local community linkage, and neighborhood patterns. In the process, LEED evaluates a building for the amount of sustainability objectives it achieves and recognizes buildings at four certification levels (Certified, Silver, Gold, and Platinum). LEED is considered to be one of the most successful green-building rating systems in the world because of its early market penetration and adoption by professionals (Xiaoping et al. 2009). As reported by USGBC, the square footage of LEED-certified construction rose 92% between 2007 and 2009.

Previous research studies investigated various aspects of building sustainable design, including the following: evaluation of available rating systems (Gowri 2004; Roderick et al. 2009; Todd et al. 2008); decision support in selecting project delivery processes in sustainable buildings (Korkmaz et al. 2010); impact of rating systems on construction industry stakeholders (Syal et al. 2007; Bayraktar and Owens 2010); implementation of building information models in sustainable building design (Chakraborty and Bahr 2009); and evaluation of the total ownership cost of green facilities (Pearce et al. 2010). As can be seen from the preceding list, very little research has studied and modeled the impact of project stakeholder interactions on the sustainable design process, especially in the predesign phase. Therefore, this paper presents the development of a model that evaluates the impact of stakeholder interactions on the sustainability goal and objective setting process in green-building projects.

Stakeholders Interviews

Various stakeholders/industry experts in the construction industry were interviewed to capture their interactions in sustainable building projects. A total of five architects/designers, six general contractors, four owners/clients/tenants, two USGBC members, and 15 suppliers/manufacturers, all of whom had previous green-building experience and have worked on at least one LEED-certified building, were surveyed for the purpose of obtaining data for this study. The survey was conducted using a semistructured questionnaire and open-ended interviews (Patton 2002). The questionnaire consisted of five broad open-ended questions that were carefully designed with specific goals, as shown in Table 1. All the interviews conducted were voice-recorded with the prior permission of the interviewees for data storage and verification for later purposes. The diverse demographics of the surveyed participants were a result of performing the interviews and completing questionnaires during a national green-building convention that was attended by a diverse audience.

The main objective of conducting open-ended interviews with industry experts is to extract as much information as possible, to comprehensively understand the interactions between various stakeholders during the eco-charrette meetings and how these interactions impact their decisions and, as a result, the sustainability of the building. Various stakeholders were approached for interviews to gauge the wide range of issues each stakeholder faces during the decision-making process of setting the sustainability goals and objectives for a building project. It was also important to examine the different measures of effectiveness the stakeholders use in determining and complying with sustainable building practices. Almost all of the stakeholders interviewed expressed that maintaining extensive documentation of the design and construction activities is one of the most common measures of effectiveness. The documentation, according to the interviewees, was mostly based on the standards and specifications described in the green rating systems. The final results of these interviews were all compiled into the agent behaviors and attributes illustrated in the following section describing the agent-based model formulation.

Table 1. Survey Questionnaire

Questions	Purpose
Who are the main construction industry stakeholders affected by the implementation of these building practices and sustainability policies?	Identify the agents for the agent-based modeling.
What are the main issues/factors that impact or are impacted by sustainable practices and decisions?	Identify the attributes of the agents previously identified.
What are the main interactions between these issues and stakeholders?	Identify the rules and behaviors of each of the stakeholders/agents.
What are the measures of effectiveness that have been set for the local implementation of sustainable building policies and practices?	Identify any policies or standards that are set or followed.
How do these interactions impact the measures of effectiveness?	Study the impact of the policy changes on the building sustainability.

Agent-Based Model Formulation

This development stage focuses on the formulation of the agent-based model after collecting all the relevant data in the previous stage. The proposed model utilizes agent-based modeling (ABM) to simulate the different stakeholders involved in the green-building predesign phase (Anumba et al. 2005). In ABM, the term agent is frequently used. There is no precise and universally accepted definition of an agent. Some claim that to be an agent, the software must have some kind of intelligence (Fenves et al. 1994). At the no or minimal intelligence end, it can be quite difficult to distinguish between an agent-oriented program and an object-oriented program. Agents can be reactive (reacting to stimuli or changes in their environment) or proactive (creating change as the result of actions taken in the pursuit of some goal) (Vlassis 2003).

Based on the conducted interviews and collected data, three main stakeholders were identified as being involved in the predesign phase of green buildings: (1) the owner, (2) the designer, and (3) the building's future users (i.e., future occupants). To develop an effective agent-based system, a plan will need to be embedded within an algorithm, and agents will need only to carry out the computations necessary to produce their own results and make contributions to an overall process (Ren et al. 2001). Accordingly, each stakeholder is represented as a *simulation agent* encompassing the identified attributes and behaviors.

In addition to the three main stakeholders, a fourth passive agent is now formulated to represent the project under design to model all the project attributes with no modeled active behavior. The following subsections will describe each of the four agents and the simulation mechanism that controls their interaction.

Project Agent

The project under design is formulated as a passive agent that has no behaviors but includes all the project design attributes and LEED credits. The scope of the model is limited to the construction of new institutional (higher-education) buildings because most of the obtained data are for institutional buildings.

The project design attributes are initially identified as the characteristics and variables that affect and define the project design. These attributes include site characteristics such as total area, distances to public transit and services, and zoning requirements; and design variables such as building footprint, number of floors, roof type (i.e., vegetated or regular), and on-site parking spaces. These design attributes are considered and controlled by the designer to achieve the best design that satisfies the owner's requirements in terms of space programming and required minimum LEED certification level.

LEED credits are then modeled in the project agent to represent the different credit categories, their interrelations, and their dependencies on the project design attributes. The proposed model utilized *LEED 2.2* (USGBC 2005), based the fact that it is a well-established and widely applied approach to quantifying and assessing the sustainability of building projects. The incorporation of the LEED credits system in the project agent involves three main elements:

1. Classification of the LEED credits;
2. Evaluating the applicability and dependency rules of the credits; and
3. Assessing the dependency of the credits on the project design variables.

The following subsections describe each of these elements in detail.

Classification of the LEED Credits

For the purpose of this study, the credits in the *LEED 2.2* system are categorized into binary and multiple-option credits. Binary credits involve a simple decision of whether to aim for achieving them without the need to consider multiple options for their achievement. Binary credits can refer to two cases:

1. Credits that depend solely on the project site conditions, such as community connectivity (SSc2) and brownfield development (SSc3); and
2. Credits with multiple options that are assumed to be binary because detailed information or analyses of their applicability is only possible during the design phase.

On the other hand, a multiple-option credit is one that can be achieved through a number of possible methods (multiple sets of criteria, the satisfaction of any of which can lead to credit achievement) and can be decided upon with the information available during the predesign phase. For example, Credit SSc4.3 (Alternative Transportation, Low Emitting & Fuel Efficient Vehicles) is classified as a multiple-option credit because it can be achieved by offering one of the following three options:

- Providing fuel-efficient vehicles for 3% of the full-time occupants;
- Providing parking for fuel-efficient vehicles; or
- Installing alternative-fuel refueling stations.

Applicability and Interdependency of LEED Credits

The formulation of the LEED credits in the project agent of the developed model considers the interrelations between the credits. In that regard, some credits represent prerequisites for the achievement of others. Some credits, although not prerequisites, directly impact the achievement of others. Table 2 lists the main interdependencies between sample LEED credits that are captured in the developed model. For example, the achievement of Credit SSc7 (Heat Island Effect-Roof) can greatly impact the decision on Credits SSc5.1 (Protect or Restore Open Space) and SSc5.2 (Maximize Open Space). If a green roof is selected to reduce the heat-island effect and earns a SSc7 credit, it can simultaneously help earn Credits SSc5.1 and SSc5.2 because the green roof can also be considered a vegetated open space. Formulating these interdependencies between credits is critical for the development of the designer agent, which will be discussed in the next sections.

Table 2. Applicability and Interdependency of Sample LEED Credits

Credit	Description	Applicable credits
SSc1	Site selection	—
SSc2	Development density & community connectivity	SSc1
SSc3	Brownfield redevelopment	SSc1
SSc4.1	Alternative transportation, public transportation access	SSc1, SSc2
SSc4.2	Alternative transportation, bicycle storage & changing rooms	SSc4.4, SSc5.2
SSc4.3	Alternative transportation, low emitting & fuel efficient vehicles	SSc4.4, SSc5.2
SSc4.4	Alternative transportation, parking capacity	SSc1, SSc4.2, SSc4.3, SSc5.2
SSc5.1	Site development, protect or restore habitat	SSc2, SSc5.2, SSc7.2
SSc5.2	Site development, maximize open space	SSc2, SSc5.1, SSc7.2
SSc6.1	Stormwater design, quantity control	SSc7.2
SSc6.2	Stormwater design, quality control	—
SSc7.1	Heat island effect, nonroof	—
SSc7.2	Heat island effect, roof	SSc6.1,SSc6.2, SSc5.1, SSc5.2
SSc8	Light pollution reduction	—

Dependency of LEED Credits on Project Design Variables

In addition to the previously formulated credit interdependencies, credits depend on building design variables that are controlled by the designer. Table 3 is a summary of the variables used in the model that affect the total LEED credits achieved either directly or indirectly. For example, the site location selection determines the credits earned pertaining to access to basic amenities and public transportation (Credits SSc2 and SSc4.1); and the building space programming (specifically the design of parking space) affects the LEED credits for reduced use of automobiles and facilitating the use of fuel-efficient vehicles (Credits SSc4.2 and SSc4.3). Also, the designer's decision to use more lighting and thermal controls helps in achieving Credits EQc6.1 and EQc6.2.

User Agent

The model represents all building users as a single agent that is assumed to encompass the collective attributes and behaviors of the building occupants. Users, or the future building occupants, provide valuable input in the decision-making process as they voice their concerns and may show some resistance to the achievement of credits that cause them discomfort or inconvenience. Some of the concerns which users have include indoor environmental quality (lighting, thermal comfort, acoustics, and ventilation) and parking

Table 3. Dependency of LEED Credits on Building Design Variables

Variables	Impact on credit
Site location	SSc1, SSc2, SSc3, SSc4.1
Site area	SSc5.1, SSc5.2
Footprint	SSc5.1, SSc5.2, SSc7.1, SSc7.2
Number of bike racks	SSc4.3
Number of changing rooms	SSc4.3
Number of alternative fuel vehicles	SSc4.2
Number of parking spots	SSc4.2, SSc4.3
Number of preferred parking spots	SSc4.2, SSc4.3
Number of lighting controls	EQc6.1
Number of thermal controls	EQc6.2
Number of door leafs	MRc7
Vegetated open space	SSc5.1, SSc5.2, SSc7.2
Green roof area	

availability (Leaman 2002; Baird 2009; Litman 2010). In the present model, the users are assumed to show resistance to decisions affecting their thermal comfort (i.e., number of thermal controls as covered by Credit EQc6.1), lighting comfort (number of lighting controls as covered by Credit EQc6.2), and the number of regular parking spaces available (Credits SSc4.3 and SSc4.4). These three factors are assumed to represent the overall comfort level and satisfaction of building users and are considered in the setting of the sustainability goals. Resistance to other design attributes, such as ventilation and natural lighting, are not considered in the present model because of the absence of the information required for assessing them in the predesign phase of the project. Examples of such missing information include detailed layout of the HVAC, the locations and orientations of building windows, and the partitioning type.

The importance or the weight of each one of these resistance/comfort factors is calculated using the analytical hierarchy process (Saaty 1980) based on a pairwise comparison of the user inputs. A short web-based survey was designed to acquire the importance of these factors from the users of an institutional building. The survey had three simple questions, which asked the users to rate the importance of one factor to another, which included the importance of thermal comfort to lighting comfort (O_{tl}), thermal comfort to parking (O_{tp}), and lighting comfort to parking (O_{lp}). For each surveyed user, the pairwise comparison weights were transformed using the analytical hierarchy process into the weights for the resistance factors for the corresponding user. These weights included the weight for thermal comfort (W_t), the weight of lighting comfort (W_l), and the weight of parking comfort (W_p). Accordingly, the average weights are calculated to represent the relative importance of the resistance factors for all the users surveyed. It is proposed that similar surveys would be performed for the potential users of specific projects because many variables could affect the relative importance of these factors to different users.

Based on the obtained weights, user overall comfort/resistance behavior to the green-building predesign is modeled as the weighted average of their acceptance of lighting, thermal, and parking comfort. The acceptance of each of these three aspects is modeled using linear utility functions that depict the deviation of the design from the user's desired level of comfort. User comfort in regard to onsite parking is calculated using Eq. (1) as a utility value (U_p) that

1. Calculates the available regular parking space (RP) as the difference between the total capacity (TP) and the preferred parking space (PP) for fuel-efficient vehicles; and
2. Obtains the ratio of the available regular parking space (RP) to the demanded space by the building users (DP).

Accordingly, users would have a low utility value (i.e., high resistance) if their demanded parking space is not satisfied because of the space allocation to preferred parking for fuel-efficient vehicles. On the other hand, user lighting control comfort (U_l) is calculated using Eq. (2) as the ratio of the number of lighting controls to the number of rooms in the building. This means that the users will have the highest comfort ($U_l = 1$) if they can change the lighting intensity in every individual room (and more than that if they can control lighting within specific parts of the room). Similarly, user thermal comfort (U_t) is calculated using Eq. (3) as the ratio of the number of thermal controls to the number of rooms in the building. Accordingly, the overall comfort of the users (U_{overall}) for the LEED predesign is calculated using Eq. (4) as the weighted average of the parking, lighting, and thermal comfort using their corresponding user weights (W_p, W_l, and W_t). As a result, users would express resistance to the green-building predesign if the calculated overall comfort were less than the user resistance threshold, which can also be acquired from the future occupant survey

$$U_p = \frac{RP}{DP} = \frac{TP - PP}{DP} \tag{1}$$

$$U_l = N_{LC}/N_{\text{rooms}} \tag{2}$$

$$U_t = N_{TC}/N_{\text{rooms}} \tag{3}$$

$$U_{\text{overall}} = U_p \times W_p + U_l \times W_l + U_t \times W_t \tag{4}$$

where U_p, U_l, and U_t = user utilities for parking, lighting, and thermal comfort, respectively; TP, PP, and DP = amount of space for total parking, fuel-efficient vehicles preferred parking, and user-demanded parking, respectively; N_{LC} and N_{TC} = number of lighting and thermal controls, respectively; and N_{rooms} = number of rooms in the building.

Designer Agent

The designer agent represents the technically competent individuals in the project team that determine the building design and select LEED credits based on the owner's requirements and the project constraints. It is assumed that a single agent can be used to represent the collective decision-making of architects, engineers, and LEED consultants, which, for the most part, is led by the architect. The attributes of the designer agent that are of concern in the predesign are of two main types:

1. The parameterized cost estimates for achieving LEED credits; and
2. The list of selected credits.

The first type of attribute, the parameterized cost estimates for achieving LEED credits, are defined here and are used in deciding which credits to pursue. For example, the designer agent includes the estimated additional cost of green roof installation, high-efficiency water fixtures, and material reuse. Various literature, industry reports, and standards provide sources for obtaining parameterized costs for achieving these credits (Syphers et al. 2003; Korkmaz et al. 2010). These data are complemented with the information made available by industry experts during the data collection phase of this study. It was also reported by the interviewed experts that initial costs are mainly considered in the selection of the credits rather than by evaluating other cost components of the whole life cycle.

The second type of attribute of the designer agent is the list of selected LEED credits that is used to keep track of the selected number of credits, the credit options, and the resulting additional cost.

Based on the data collection phase and the surveyed experts, the designer agent is formulated to mimic the behavior of architects and engineers during the project predesign phase. The designer agent is designed to have four main behaviors:

1. Project initial configuration behavior;
2. Credit evaluation behavior;
3. Credit maximization behavior; and
4. Credit removal behavior.

The following subsections describe in detail each of these behaviors.

Project Initial Configuration Behavior

The early behavior of the designer agent is to plan the project's initial configuration and layout to satisfy zoning requirements and owner space needs. According to the zoning requirements at the project location, the maximum number of floors, the minimum parking space required, and the minimum open space on the project site are determined. Further, the building footprint, the parking size, the type of parking (free parking outside project site, outdoor parking on site, garage parking), and the available indoor space are determined. This initial configuration of project space is used as a starting point of the predesign phase after satisfying the hard constraints of zoning and the owner's requirements. Accordingly, this initial configuration is changed by adding the space requirements of different LEED credits, such as outdoor vegetated areas and preferred parking for fuel-efficient vehicles.

Credit Evaluation Behavior

This behavior corresponds to the decision-making process of the designer in evaluating individual LEED credits. The general goal of the credit evaluation behavior is to achieve the credit under evaluation with the lowest possible cost. The evaluation behavior depends on the type of credit and whether it is a binary or multiple-option credit. If a binary credit is under evaluation, the designer would decide to select it if the owner asks to include it in the project scope. Accordingly, the evaluation of this type of credit yields the total selected credits and their costs, which would be included in the computed additional cost for LEED certification. The evaluation of multiple-option credits, on the other hand, is more complex because it requires evaluating the possibility of selecting each option for each credit and its cost implications. The designer checks the possibility of selecting each option depending on the project conditions and constraints. Accordingly, the designer selects the feasible credit options with the least cost to achieve the credit under evaluation. For example, the Alternative Fuel Vehicles credit [SSc4.3 (Sustainable Sites)] has four alternative options: provide fuel-efficient vehicles; provide preferred parking; provide alternative refueling stations; or do nothing.

Credit Maximization Behavior

The credit maximization behavior is designed to mimic the designer's initial analysis of the project to achieve the maximum number of credits while neglecting any budget or user-comfort constraints. Based on the surveyed experts, the project designer analyzes the list of LEED credits in a sequential order, starting from the sustainable site credits through the environmental quality credits, and attempts to select the maximum number of credits possible. This is achieved by executing the credit evaluation behavior on each credit while only considering the project spatial and design attributes and neglecting the budget constraints imposed by the owner and the comfort constraints imposed by the users. While going through the list of credits, the designer also considers the interdependencies between various credits and makes design decisions that maximize the credits achieved from interdependent credits. The number of selected credits is then revised considering the targeted certification level, the owner's budget, and the user's comfort, which will be described in the owner agent behavior.

To provide insight into how the decision to pursue one credit influences the evaluation of other credits, this dynamic can be explained through the simultaneous examination of the credits pertaining to green roof, maximizing of open space, and restoring of natural habitat. According to the LEED rating manual (USGBC 2005), credits such as Reduced Site Disturbance: Protect or Restore Open Space (SSc5.1), and Reduced Site Disturbance: Maximize Open Space (SSc5.2), are impacted by the decision to pursue the Landscape & Exterior Design to Reduce Heat Islands, Roof (SSc7.2) credit. In the simulation process, when the LEED credits are evaluated in sequence, Credits SSc5.1 and SSc5.2 are checked against the standards to determine if they are achievable. Further, when the simulation reaches the point where SSc7.2 is evaluated, there are two possible approaches that are captured and modeled. The owner decides what type of roof should be installed on the building. The owner can choose to have a high emissivity roof installed, a vegetated roof, or a combination of both. If the decision is to have a high emissivity roof, based on the owner's perception that it is much cheaper to install a nongreen roof compared with a vegetated roof, it is checked for compliance with the standards and the credit selected accordingly. If the owner decides, on the other hand, to have either a vegetated roof (green roof) or a combination roof, the simulation reevaluates the Credits SSc5.1 or (and) SSc5.2 to determine if they are achievable. If either of the credits (SSc5.1, SSc5.2) is not achievable, Credit SSc7.2 helps in achieving these credits.

Credit Removal Behavior

The designer in this behavior removes any extra credits that are not required to achieve the required LEED certification level. The generated number of credits from the credit maximization behavior can be greater than that required to achieve the targeted LEED certification level. Accordingly, the owner would request the designer to remove unnecessary credits in a way that simultaneously results in the greatest cost savings. In the credit removal behavior, the designer scans all the selected credits and removes the ones with the greatest additional cost. As a result, the number of total credits is reduced and the additional cost of LEED credits selected is adjusted. As described in the "Owner Agent" section, there may be a need to remove only the credits that relate to user comfort: thermal comfort (Credit EQc6.1), lighting comfort (Credit EQc6.2), and parking comfort (Credits SSc4.3 and SSc4.4). The decision to remove these credits is made by the owner agent, as described in the credit refining behavior in the following section.

Owner Agent

The owner agent is formulated to include three main attributes that describe the desired project outcomes and one behavior that ensures that these requirements are met by the designer agent. These attributes are as follows:

1. Targeted LEED certification level that is initially set based on the history of previous similar projects or based on the governmental requirements imposed on public institutions;
2. Budget allocated for seeking LEED certification, which is the amount that will be added by the owner to the original budget for constructing a regular building; and
3. Design requirements to represent building space programming and the desire to seek certain binary LEED credits.

In addition to these attributes, the owner agent includes one main behavior (called the credit refining behavior), which is described in the following subsection.

Credit Refining Behavior

The function of the credit refining behavior is to revisit the credits selected in the credit-maximizing algorithm to consider the targeted certification level, the imposed initial budget, and user resistance. The credit maximization behavior requires the designer agent to select the maximum credits possible within the given owner requirements and site characteristics. The generated list of LEED credits is evaluated in the credit refining behavior in terms of the certification level they could achieve, their associated cost, and their degree of acceptance by building occupants. Based on this evaluation, specific actions may be performed to reach the best possible scenario.

After user comfort is calculated and the credit maximization algorithm achieves the maximum number of credits, the model finally checks for the three constraints that need to be satisfied: (1) credits, (2) budget, and (3) user utility. For each of these constraints, there are two possible outcomes: over (or equal) and under, as shown in Fig. 2. Hence, the owner agent during the credit refining behavior can experience one of the following five main case situations, which represent the dynamic balancing of stakeholders' decisions and the priorities among the design objectives (budget, certification level, and user's comfort):

- Case 1 occurs when the maximum number of credits is not sufficient to achieve the targeted certification level. In this case, the targeted certification level is not realistic or feasible because of the conflict between the owner's space needs and site conditions and the LEED certification requirements. Accordingly, the owner needs to lower the targeted certification level or the required space for intended operations.
- Case 2 occurs when the maximum number of credits is above the required level, the cost is over budget, and users express resistance (i.e., utility is below the requested threshold). This case involves two problems: the cost is over budget and the users display resistance. Considering that owners usually give higher priority to the cost than to user comfort, the owner in this case would attempt to convince the users to lower their comfort threshold. As a result, the user comfort/resistance threshold is lowered by a fixed increment that is a parameter defined by the model user. Accordingly, user resistance is reevaluated and the credit refining behavior is repeated until the status changes to Case 3, which is explained next.
- Case 3 occurs when the maximum number of credits is above the required level, the cost is over budget, and user comfort is achieved. In this case, the owner would request the designer to remove a credit that would result in the greatest cost savings. Accordingly, the owner agent reruns the credit refining behavior on the revised predesign, where credits continue to be removed until either the cost is under budget (i.e., Case 5) or the targeted certification level cannot be achieved within the imposed budget (i.e., Case 1).
- Case 4 occurs when the maximum number of credits is above the required level, the cost is under budget, and users express resistance. The owner requests the designer to remove a credit that contributes to the user resistance. Accordingly, the owner agent reruns the credit refining behavior on the revised predesign, where credits continue to be removed until user resistance is removed and the revised predesign falls under Case 5.
- Case 5 occurs when the design accomplishes the predesign objectives of achieving the targeted certification level within the allocated budget while achieving the required level of user comfort.

Overall Simulation Algorithm

The overall simulation algorithm of the ABM model defines the relationships between agents and the triggers and outcomes of their behaviors, as shown in Fig. 3. The simulation starts with the project's initial configuration behavior determined by the designer agent to calculate site and building space considering the owner's operational needs and zoning requirements. This initial configuration is then manipulated by the credit maximization and credit evaluation behaviors to generate the list of the maximum LEED credits that can be selected. The owner agent, through its credit refining behavior, decides on changes to the building predesign and selected LEED credits considering the available budget for achieving LEED certification and user comfort. The decisions to change the selected credits through the credit refining behavior requires further communication with the designer (i.e., credits removal behavior) and the

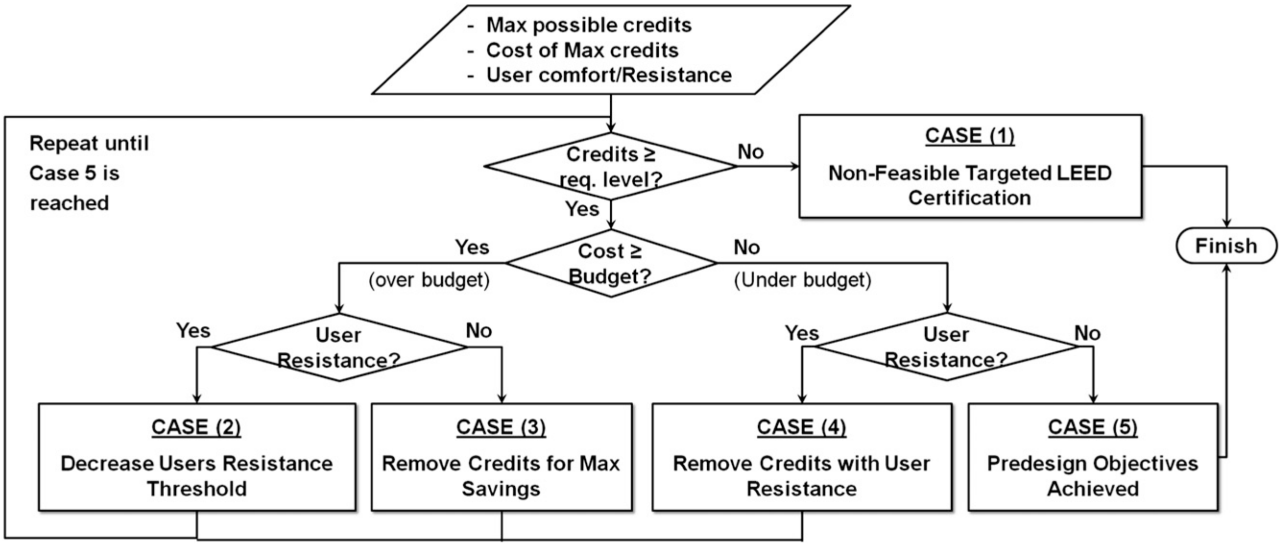

Fig. 2. Credits refining behavior of the owner agent

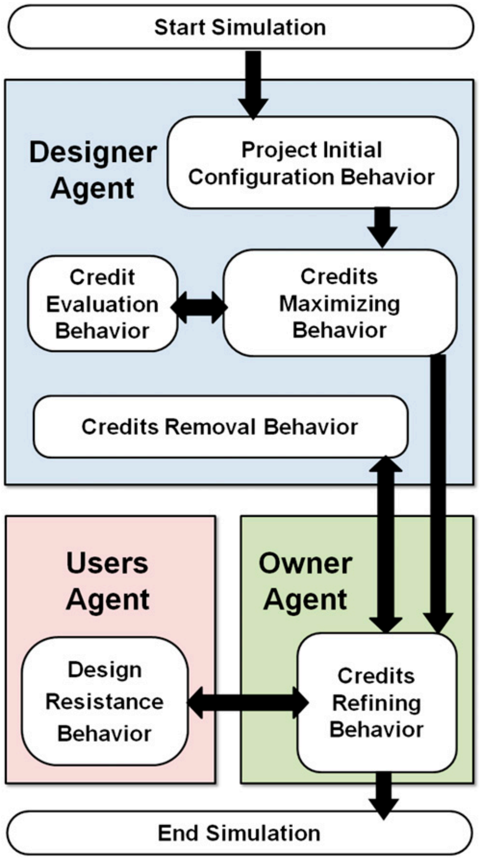

Fig. 3. Simulation of overall mechanism

users (user resistance behavior). The simulation session ends when the credit refining behavior reaches one of two possible results:

1. The targeted certification level is not found feasible within the set budget; or
2. The certification level is found achievable within the set budget.

ABM Implementation

The implementation of the previously described ABM formulation involves the selection and utilization of the ABM implementation toolkit, model verification and validation, and evaluation of the results of the case study and sensitivity analysis. The following subsections describe each of these implementation steps:

Selection of ABM Implementation Toolkit

The proposed model is developed using the Recursive Porous Agent Simulation Symphony (*Repast-S*) software package (North and Macal 2007), which is a well-recognized ABM implementation toolkit that has been utilized in various social and complex systems problems. *Repast-S* has the capacity to model the complexities of agent behaviors but is, at the same time, equally complex in terms of model development. However, *Repast-S* provides a user-friendly graphical user interface, which is easy to use and facilitates building any complex model.

When the ABM model is simulated initially, there are inputs to the model that are provided by the model user to simulate the eco-charrette process. The input data can be broadly classified into the following five categories:

1. Project specifications,
2. Owner requirements,
3. Cost data,
4. LEED credit-specific data, and
5. User resistance data.

Project specifications include the data related to the project site location, type of project, and area requirements on the site, such as total site area, building footprint, owner's required gross functional area, and parking area. Owner requirements include data such as the decision to pursue LEED binary credits, the initial budget allocated, and the target level of LEED certification. Cost data include the parameterized estimated additional costs to achieve LEED credits. LEED credit-specific data include data that is specific to each LEED credit, and is vital in the evaluation of the credit. These LEED credit data are evaluated against the LEED standard requirements to check whether they comply with the standard and are used to select credits accordingly.

The model outputs consist of the LEED credits that were selected, the additional cost to achieve these LEED credits, and the constraints on the achievement of these LEED credits. Further, the model also provides the detailed additional costs for each of the selected credits. The significance of these outputs is that they provide a better understanding to the stakeholders of what sustainable building construction involves, namely (1) which LEED credits should be targeted, (2) what credits would have impact on other credits, and (3) what the cost implications would be of the level of certification the stakeholders may wish to attain. Iterating the simulation process multiple times would give the stakeholders insight into various scenarios whereby they can achieve various LEED credits based on the constraints they may propose for cost and building-occupant resistance.

Verification, Validation, and Performance Evaluation

Verification and validation are essential components of the model development process if models are to be accepted and used to support decision-making (North and Macal 2007). To begin, various verification techniques were used to ensure that the present model is performing the duties it is intended to perform. Utilized verification techniques included review of the model flow charts and implementation code. Next, the effectiveness of the model in providing accurate results of the system being modeled was validated (North and Macal 2007). Utilized validation techniques included agent validation, data validation, process validation, and output validation (North and Macal 2007). In addition to the verification and validation process previously explained, the case-study methodology was adopted to verify and validate the model. Further, interviews with industry experts were conducted to verify that the model being developed resembled real-world situations. For the purpose of this study, the Roger Gatewood Wing, the Mechanical Engineering addition at Purdue University in West Lafayette, Indiana, was taken as the primary case study to verify the model by communicating the model output with the project owner and designer. In addition to the case study, a sensitivity analysis was performed to understand the impact of different project variables on the performance of the model. The following subsections describe in detail the results of the case study and the sensitivity analysis.

Case Study of Roger Gatewood Wing at Purdue University's Mechanical Engineering Building

The Roger Gatewood Wing, an addition to the Mechanical Engineering Building centrally located in the Purdue University campus, is a $34.5 million state-of-the-art institutional building and the first LEED-certified building on campus. The building design aimed for

LEED Silver and higher ratings by planning for the achievement of extra LEED credits during the construction process. This institutional building is adding 3,809 m^2 ($\sim$41,000 sq ft) of assignable space to the Mechanical Engineering Building and is increasing the existing space by 55%. A total of 41 LEED credits were anticipated toward the completion of this project. In the eco-charrette meeting during the predesign phase of this project, the Purdue Facilities Team along with the design firm came up with a summary of LEED credits that could be achieved. This checklist of LEED credits, along with the costs associated with achieving them, was obtained from the designer and used in the validation process of the model developed in this study.

All the relevant site characteristics and parameterized costs of different credits were collected and used by the proposed model. Not all of the LEED credits have additional costs associated with their achievement. Many of them are achieved based on site selection and other project characteristics. Taking into account the large amount of data collected in this study from industry expert interviews and from a comprehensive survey of the literature and web resources, the parameterized costs for achieving LEED credits were accumulated and used in the model for calculating the additional LEED costs. The costs were defined by the model user and were converted to unit costs and used in the calculations involved in the model. Further, there were also estimated soft costs associated with the LEED certification process of this building. A number of soft-cost items were anticipated: performing the energy modeling to achieve the optimize energy performance credit; LEED consulting and documentation cost for the designer; contractor's LEED costs (probably included in their bids); and cost for building commissioning.

The developed agent-based model generated output that closely matches the real performance of the case study. The total number of generated credits was 41, which included nine sustainable-site credits, three water efficiency credits, six energy credits, six materials credits, 12 indoor environment quality credits, and five innovation credits. In the actual scenario, the building was anticipated to achieve at least 39 credits, with the total upfront additional cost estimated for the building to be LEED-certified to stand between $1,075,000 and $1,550,000. The owner and the designer of the project reviewed and validated the model output and indicated its usefulness in effectively modeling the sustainability goal setting process of the predesign phase of LEED buildings. The validation of the model output was performed by arranging individual meetings with the project owner and designer to compare the generated and actual values of the project credits and cost.

Sensitivity Analysis

The model variables were assessed to determine their level of impact on the outcomes of the model. The assessment showed that some variables had a pronounced impact on the number of credits selected and the additional LEED costs estimated for the predicted level of certification. Sensitivity analysis was performed on two of the important model parameters for the Gatewood Wing case study:

1. Initial budget and target level of certification (owner requirements); and
2. Footprint and type of roof (project specifications).

Effect of Initial Budget and Target Level of Certification

As illustrated in the preceding, the ABM model was formulated such that the required target was achieved when the additional LEED cost was under the budget allocated for certification, the total number of LEED credits selected was greater than the minimum required for a particular certification level, and there was no resistance from users expressed in terms of their average utility. In this sensitivity analysis, all the model parameters were kept constant and only the two considered types of input data (the budget allocated for the project and the target level of certification) were varied to examine their impact on the model results.

Table 4 shows the results for the different initial budgets and target levels of certification used in this sensitivity analysis. The Gatewood Wing, as previously mentioned, was anticipated to achieve LEED certification, but from the eco-charrette meeting it was decided to pursue a LEED Silver certification because of the possible achievement of more LEED credits during construction. The model suggests that the building could even achieve a LEED Gold certification as a result of the owner setting a certification budget of $1.5 million (ultimately an actual cost for certification of $1,468,243).

Effect of Building Footprint and Roof Type

The building footprint and total site-area model parameters were varied in combination to show their effect on the simulation output. Keeping all other model parameters constant, the type of roof was varied and a number of simulation runs were performed. The footprint/total site area was varied from 0.2 [footprint = 929 m^2 (10,000 sq ft), total site area = 4,645 m^2 (50,000 sq ft)] to 1.0 [footprint = total site area = 4,645 m^2 (50,000 sq ft)]. Fig. 4 depicts the impact of the building footprint on the total LEED credits achieved and its impact on the total estimated additional cost of LEED certification. The main findings of this sensitivity analysis are presented in the following paragraphs:

When the model was run with the decision to install a green roof, the selected LEED credits ranged from 43 when the footprint was the smallest, to 37 when the footprint was equal to the site area. For all the simulation runs, the initial budget was fixed at $1.5 million; however, the estimated additional LEED cost ranged from $1.3 million to $1.49 million. Initially, when the footprint was small, there was a vegetated open space large enough to achieve LEED credit without needing the green roof area. Further, because the green roof was being installed, a total of three credits (SSc5.1, SSc5.2, and SSc7.2) were achievable. Because the green roof cost was dependent on its area, the initial additional cost was also within the budget. As the footprint area increased, the green roof area was required to compensate for the lost vegetated open space and therefore the additional cost tended to exceed the budget. Hence, credits were removed by the credits removal process in order to reduce cost and stay within budget. This explains the decrease in credits with the increase in footprint area. The additional cost for certification kept increasing with the footprint because the LEED cost was directly related to the green roof area; but when the footprint equaled one-half the site area, the cost exceeded the initial budget ($1.5 million) and extra credits therefore were removed by the model to reach the target budget. Successively, when the entire simulation was run for a nongreen roof, the additional cost was significantly less compared with runs that contained the green roof. This is attributed to the fact that the upfront costs of installing a green roof were very high compared with installing a high emissivity roof,

Table 4. Sensitivity of Achieving LEED Certification Levels on Project Cost

Achieved LEED credits	Maximum certification level	Additional LEED cost (U.S. dollars)
41	Gold	1,468,243
39	Gold	1,114,443
38	Silver	822,818
37	Certified	755,318

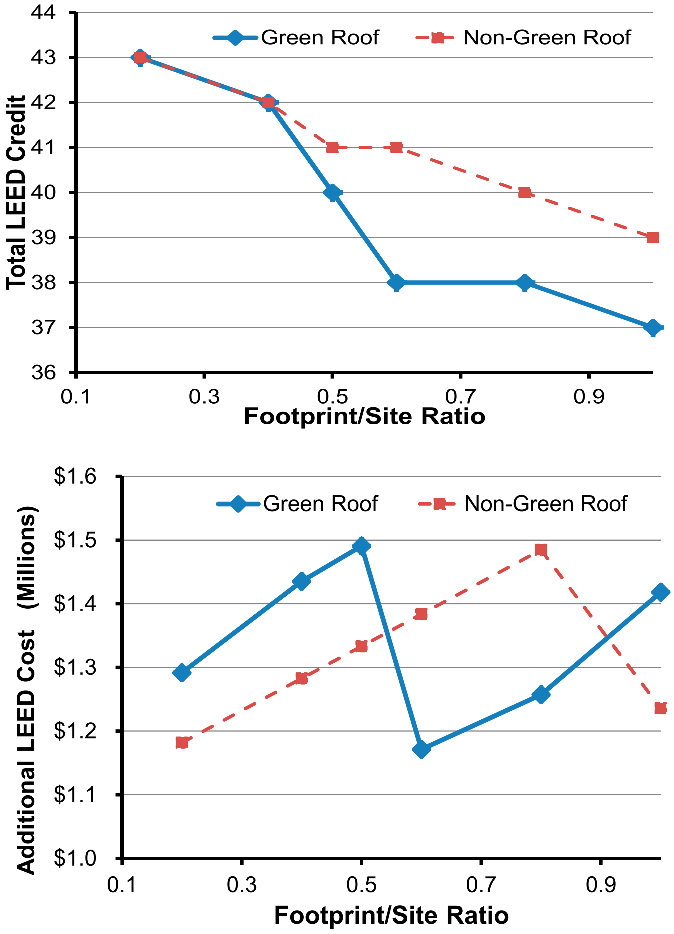

Fig. 4. Impact of footprint/site area ratio on total LEED credits and cost

stemming from the stronger structural system required to support the load of the green roof. Also, a higher number of LEED credits was achieved because the decision to go with a nongreen roof nullified the impact the roof credit would have on site-development credits and storm-water quality credits. The additional cost was well under budget until the footprint/site area ratio was 0.8. In this case, the extra credit with maximum additional cost was removed to bring down the cost to within the initial budget.

The building footprint not only impacted the green roof area but also dictated the amount of available space on the project site for outdoor parking, bike racks, and sidewalks (site hardscape). The increase in the building footprint made some credits achievable as discussed previously in this article (reduced site disturbance credits and green roof credit); but because of the decrease in available outdoor space, the credits related to parking area, bike rack area, and site hardscape area (which fall under the Sustainable Sites category) were not selected. This explains the decrease of selected credits in Fig. 4 even when the additional cost was within the initial budget. Further, the additional cost for the green roof credit [$323/m^2$ ($30/sq ft)] was very high compared with the high emissivity roof [$32.3/m^2$ ($3/sq ft)] which led to credits being removed because of the decision to pursue the green roof credit (to remain within budget). The credits removed in this case were related to optimizing energy performance because they accounted for a high additional cost. When the choice was made to have a high emissivity roof rather than a green roof, the additional cost stayed well within the initial budget and the credits that could be affected by budget constraints were not removed. The increase in the building footprint reduced the Sustainable Sites credits, but because the additional cost was within the budget, other credits were not removed. This explains the larger number of LEED credits selected in the case of the nongreen roof compared with the green roof scenarios.

Summary and Conclusion

This paper presented the development of an agent-based model for simulating the interactions between project stakeholders in setting the sustainability goals and objectives of construction projects during the predesign phase of the project life cycle. The model was built based on a set of interviews conducted with industry professionals and project stakeholders involved in the design and construction of sustainable buildings. As a result of these interviews, the main agents to be incorporated in the model were identified and included: designer agent; owner agent; user agent; and project agent. Along with these main agents, a number of behaviors were also identified. The developed model was then tested using a detailed case study of the Roger Gatewood Wing project of the Mechanical Engineering Building at Purdue University. Furthermore, the model performance was validated through a systematic sensitivity analysis to investigate the impact of project input change on the generated results.

The proposed model would contribute to the construction industry by helping building-owners in strategically setting their sustainability goals and assessing the feasibility of seeking certain certification levels. Furthermore, the model provides better understanding and formulation of green-building design, in terms of the relations among design parameters, sustainability rating achievement, project budget, and user comfort.

However, the developed model is not without limitations, which are detailed as follows.

Limitation 1

The developed agent-based model is a proto-agent model. Currently, these agents do not have advanced learning or negotiation capabilities. Because the present model is part of the development of a larger model that assesses the impact of the adoption of sustainable practices on the construction industry, this limitation will be addressed by adding learning capabilities to the present agents as they interact in a larger-scale environment (with multiple projects running). At the present stage, the aforementioned larger model has continued to focus on the project scale by quantifying the actual environmental impacts of selected credits through life-cycle assessment, and modeling the eventual implementation of selected credits during the construction phase and the causes for discrepancy between selected and implemented credits. At the market/region scale, the present work is focusing on modeling the factors impacting the diffusion and adoption of sustainability rating systems and their aggregate impacts on the triple bottom line.

Limitation 2

Another limitation of the present model is that it was specifically designed for evaluating the selection of LEED credits. This limitation is going to be addressed in the planned future research efforts of this research team.

Limitation 3

The model can be refined in the future by modeling the individual stakeholders instead of consolidating them in a single agent (i.e., representing all building users in a single simulation agent).

Finally, the present model is limited to modeling the interactions of stakeholders in the predesign phase of the project. Therefore, the research team plans to extend this model to the design and construction phases of the project life cycle.

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