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OPTIMIZING SELECTION OF EXISTING BUILDING UPGRADES TO MAXIMIZE THEIR SUSTAINABILITY

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Abstract: Existing buildings are often in urgent need for upgrading to improve their performance in terms of energy and water consumption, as well as carbon emissions. Building owners and operators often allocate budgets to upgrade their buildings and they always seek identification of building upgrades to improve performance of their buildings and achieve green certification. This paper presents the development of an optimization model that is capable of identifying building upgrades to achieve green certification for existing buildings. While several green certification programs are currently available for existing buildings, this paper focuses on Leadership in Energy and Environmental Design (LEED) rating system for existing buildings. The optimization model is developed in three main steps, including model formulation step that focuses on model decision variables, objective function, and constraints; computational step that focuses on selecting optimization algorithm and implementing the model calculations; and evaluation step that focuses on testing and refining the model performance. A case study of an existing building is used to demonstrate the model capabilities. The optimization model was able to identify the optimal selection of buildings upgrades to achieve LEED certification for existing buildings with minimum upgrade budget or maximize the sustainability of the building within a specified budget. The optimization model is expected to support decision makers, building owners, and operators to identify optimal selection of upgrades to improve performance of existing buildings and achieve sustainability certification programs.

1 INTRODUCTION

As the environmental impacts of buildings increased in the past few decades, building sustainability has been continuously promoted in various standards. One such standard that has been gaining popularity throughout the world and particularly in the United States is the Leadership in Energy and Environmental Design (LEED) rating systems. LEED rating systems are developed by the United States Green Building Council (USGBC) to improve the performance of new and existing construction in six major areas. These areas include: sustainable sites, water efficiency, material and resources, indoor environmental quality, energy and atmosphere, and innovation in operations/design (USGBC 2014). Recently, the USGBC reported that more than 20 billion square feet of building spaces are LEED-certified worldwide (U.S. Green Building Council 2016). Most of the LEED certified square feet currently fall into the category of new construction, however, there is a growing trend in more recent years to promote LEED certifications for existing buildings, especially aging ones, to improve their environmental, economic, and operational performance (Stuart Kaplow 2015). Often times when existing buildings are considered for renovation and green certification, budgets are allocated for the building upgrades. These budgets drive decision makers to identify and implement the most cost-effective credit areas to pursue LEED certification. Furthermore, most owners are interested in receiving the most benefit out of their investment. Other decision makers are interested in achieving specified LEED certification with minimum upgrade cost. To support these needs, there is a pressing need to develop models that can identify optimal selection of building upgrades not only to improve the performance of existing facilities but also to embrace the highest certification levels with minimum cost or within available upgrade budgets.

The LEED rating system for existing buildings is divided into seven main divisions: Sustainable Sites (SS), Water Efficiency (WE), Energy and Atmosphere (EA), Material and Resources (MR), Indoor Environmental Quality (IEQ), Innovation in Operation (IO), and Regional Priority (RP). Each of these seven divisions is divided into subdivision(s) which determines what items need to be fulfilled in order to earn LEED credits, as shown in Table 1 and Table 2. A LEED certified project should fulfill all the prerequisites and earn a sufficient number of points to achieve the desired certification level. Four certification levels are available for ranking green buildings using the LEED rating system: (1) certified level which requires 40 – 49 points; (2) silver level which requires 50 – 59 points; (3) gold level which requires 60 – 79 points; and (4) the platinum level which requires 80 points or more, as shown in Figure 1 (USGBC 2013).

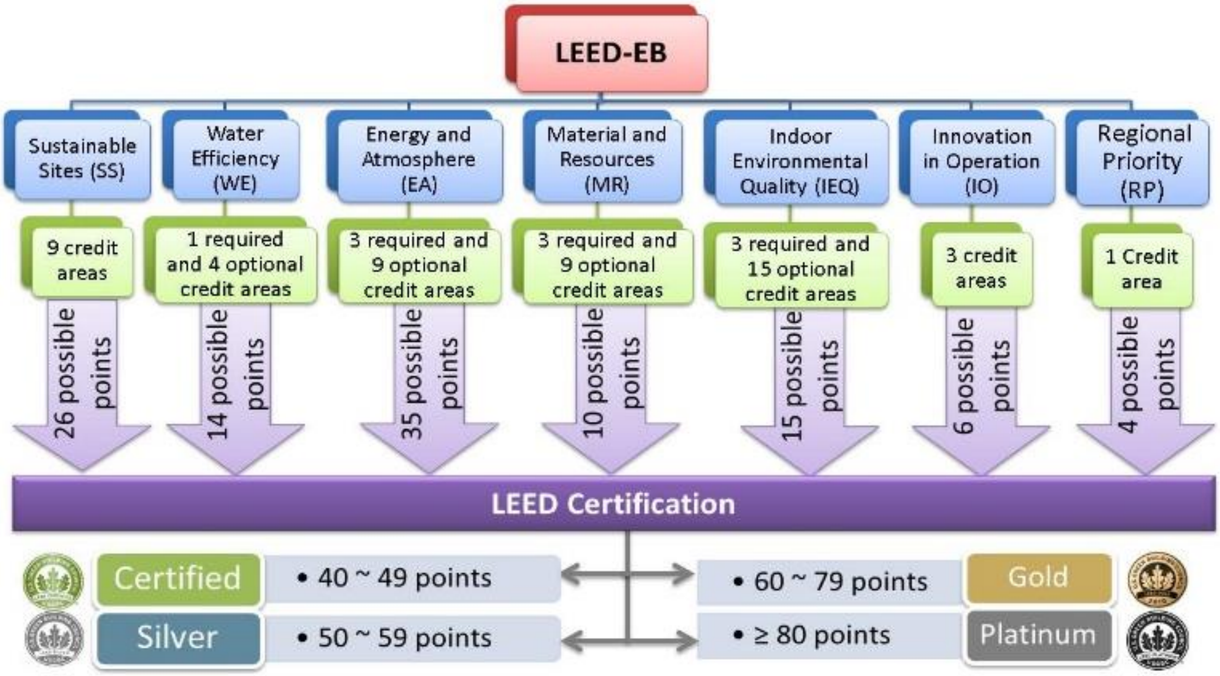

Figure 1: LEED-EB rating system and certification requirements

Several studies have been conducted to evaluate the performance of sustainable buildings. For example, a recent study evaluated 11 LEED certified buildings and analyzed their energy and indoor water usage. Furthermore, it compared these buildings to the design estimates and to the averages of existing commercial buildings. This study showed that six of the considered buildings use less energy than what was estimated during the design phase. The energy consumption of these buildings was also evaluated and it was concluded that all buildings provide an average of 40% energy savings compared to their initial baseline. Based on the LEED buildings that applied for water reduction, the conducted study showed that the actual consumption compared to the initial baseline produced an average water savings of 13% (C. Turner 2006). Another research study also focused on measuring the performance of post-occupancy LEED projects. This study examined the performance of 25 Illinois LEED-NC Projects in terms of energy performance, greenhouse gas emissions, water use, commute transportation, construction & operating costs, occupant comfort and health. This study compared the performance of these LEED projects to the

Commercial Building Energy Consumption Survey (EIA 2006). The study found that these LEED projects perform better in energy efficiency than the national average for all commercial buildings (EIA 2006) with an average improvement of 24%. The study also reported that a building with higher energy optimization points consumes less energy and performs better. This study reported that the energy consumption of the analyzed buildings caused 70% of their CO2 emissions, and accordingly the achieved reduction in energy consumption generated significant reductions in their CO2 emissions (USGBC 2009).

Table 1: Divisions of LEED Rating System for Existing Buildings (USGBC 2013)

#	Subdivisions	Max. possible points
	Sustainable Sites (SS) (26 Possible points)	
1.0	LEED Certified Design and Construction	4
2.0	Building Exterior and Hardscape Management Plan	1
3.0	Integrated Pest Management, Erosion Control, and Landscape Management Plan	1
4.0	Alternative commuting transportation	15
5.0	Site Development-Protect or Restore Open Habitat	1
6.0	Stormwater quantity control	1
7.1	Heat island reduction-nonroof	1
7.2	Heat island reduction-roof	1
8.0	Light pollution reduction	1
	Energy and Atmosphere (EA) (35 Possible points)	
P1*	Energy Efficiency Best Management Practices—Planning, Documentation, and Opportunity Assessment	Required
P2*	Minimum energy efficiency performance	Required
P3*	Fundamental refrigerant management	Required
1.0	Optimize energy efficiency performance	18
2.1	Existing Building Commissioning-Investigation and Analysis	2
2.2	Existing building commissioning-implementation	2
2.3	Existing building commissioning-ongoing commissioning	2
3.1	Performance measurement-building automation system	1
3.2	Performance measurement-system level metering	2
4.0	On-site and Off-site Renewable Energy	6
5.0	Enhanced refrigerant management	1
6.0	Emissions reduction reporting	1
	Materials and Resources (MR) (10 Possible points)	
P1*	Sustainable purchasing policy	Required
P2*	Solid waste management policy	Required
1.0	Sustainable purchasing-ongoing consumables	1
2.0	Sustainable purchasing-durable goods	2
3.0	Sustainable Purchasing-Facility Alterations and Additions	1
4.0	Sustainable Purchasing-Reduced Mercury in Lamps	1
5.0	Sustainable purchasing-food	1
6.0	Solid waste management-waste stream audit	1
7.0	Solid waste management-ongoing consumables	1
8.0	Solid waste management-durable goods	1
9.0	Solid Waste Management-Facility Alterations and Additions	1

*P: Prerequisite for acquiring a LEED certificate

Table 2: Divisions of LEED Rating System for Existing Buildings Cont'd (USGBC 2013)

#	Subdivisions	Max. possible points
	Indoor Environmental Quality (IEQ) (15 Possible points)	
P1*	Minimum indoor air quality performance	Required
P2*	Environmental tobacco smoke (ETS) control	Required
P3*	Green cleaning policy	Required
1.1	Indoor air quality best management practices-indoor air quality management program	1
1.2	Indoor air quality best management practices-outdoor air delivery monitoring	1
1.3	Indoor air quality best management practice-increased ventilation	1
1.4	Indoor Air Quality Best Management Practices-Reduce Particulates in Air Distribution	1
1.5	Indoor Air Quality Best Management Practices-Indoor Air Quality Management for Facility Alterations and Additions	1
2.1	Occupant comfort-occupant survey	1
2.2	Controllability of Systems-Lighting	1
2.3	Occupant comfort-thermal comfort monitoring	1
2.4	Daylight and Views	1
3.1	Green cleaning-high performance cleaning program	1
3.2	Green cleaning-custodial effectiveness assessment	1
3.3	Green Cleaning-Purchase of Sustainable Cleaning Products and Materials	1
3.4	Green cleaning-sustainable cleaning equipment	1
3.5	Green Cleaning-Indoor Chemical and Pollutant Source Control	1
3.6	Green cleaning-indoor integrated pest management	1
	Water Efficiency (WE) (14 Possible points)	
1.0	Minimum Indoor Plumbing Fixture and Fitting Efficiency	Required
2.0	Water performance measurement	2
3.0	Additional Indoor Plumbing Fixture and Fitting Efficiency	5
4.0	Water efficient landscaping	5
5.0	Cooling tower water management	2
	Innovation in Operations (IO) (6 Possible points)	
1.0	Innovation in Operations	4
2.0	LEED accredited professional	1
3.0	Documenting sustainable building cost impacts	1
	Regional Priority (RP) (4 Possible points)	
1.0	Regional priority	4

*P: Prerequisite for acquiring a LEED certificate

A number of research studies focused on quantifying the impacts of implementing green measures on building performance. These studies include research that focused on: studying the impact of implementing wind and solar energy systems to offset building energy demand (e.g. Chapman and Wiczkowski 2009; James et al. 2011; Matthews et al. 2004; Pruitt 2001), and Installing energy efficient HVAC and geothermal heat pumps for heating and cooling in buildings (e.g. Bloomquist 2001; Chiasson 2006; Long Ni et al. 2011; Pardo and Thiel 2012). With regard to water use, research studies focused on the use of water efficient plumbing fixtures in residential buildings (e.g. GAO 2000) and the use of solar water heaters for commercial buildings (e.g. Hasan et al. 2004; Pannila 1993; Raisul Islam et al. 2013; Sebnem 1992). In terms of LEED certification, several studies focused on (1) environmental and economic benefits of embracing LEED practices in buildings (e.g. Alborzfard 2012; Mohan and Loeffert 2011; Mosteiro-Romero et al. 2014; Reichardt 2014; Turner and Chan 2013; Wagner and Nobe 2012); (2) effect of LEED certification on reducing energy consumption and greenhouse gas emissions (e.g. Newsham et al. 2009; Scofield 2013); and (3) role of green building measures on health and wellbeing of the building occupants (e.g. Allen et al. 2015; Singh et al. 2010).

Additional studies focused on developing tools and systems to support building owners in achieving and fulfilling LEED credits areas. (Marzouk, Abdelhamid, and Elsheikh 2011) developed an optimization model that can maximize the number of earned LEED points based on building materials. (Marzouk, Abdelhamid, and Elsheikh 2011) utilized ant colony optimization and system dynamics to identify optimal materials for construction such as windows, carpets, and roofs. However, the study conducted by (Marzouk et al. 2011) was limited to major renovations and new construction and did not consider material selection for LEED-EB. Another similar study conducted by (Barnes and Castro-Lacouture 2009) identified the optimal selection of building material, equipment and systems in existing structures. (Barnes and Castro-Lacouture 2009) study was however limited to items that could be created in a Building Information Modeling (BIM) environment and as such did not consider LEED-EB credit areas such as light pollution.

(Juan, Gao, and Wang 2010) focused on creating a decision support system that can analyze trade-offs among renovation cost, building quality, and environmental impacts. This system was capable of generating an optimal list of upgrades for a case study of an office building where the results of the system were compared to traditional engineering practice to demonstrate the system capabilities. While the model provided promising results, it did not consider (1) all LEED-EB credits; (2) the energy consumption of all building fixtures and equipment; and (3) multiple alternatives for improving performance of building systems. Another tool was created to mainly optimize upgrade decisions for army facilities where the user creates an estimate of the life cycle cost for the desired and applicable LEED-EB credits. With the implementation of linear programing, the building data is used to determine the most cost-effective path to achieve the desired LEED-EB certification (Bastian 2011). While the model enabled owners to optimize LEED-EB certification costs, its scope was limited as it is unable to (1) model building fixtures and equipment that consume water and energy; (2) calculate water and energy costs based on feasible upgrade measures; (3) use building expected performance obtained from implementing green building measures to calculate LEED-EB credit points; and (4) identify upgrade decisions that are needed to meet the minimum requirements for water and energy performance in LEED-EB. Another optimization model was developed to minimize upgrade cost to achieve LEED certification for existing buildings (Abdallah, El-Rayes, and Liu 2016). (Abdallah, El-Rayes, and Liu 2016) model is designed to identify optimal selection of building upgrades to achieve a specified LEED-EB certification level regardless of the available budget for the building upgrades. For example, (Abdallah, El-Rayes, and Liu 2016) model can identify the minimum possible upgrade cost to achieve Gold certification in the LEED-EB rating system. (Abdallah, El-Rayes, and Liu 2016) model focused on achieving LEED-EB certification and is not capable of maximizing the sustainability of existing buildings by maximizing the number of earned LEED-EB points within a specified upgrade budget.

Despite the significant contribution of the existing research studies, the existing models have limited capabilities in optimizing upgrades for existing buildings. The existing models do not have the capability to analyze and optimize (1) the selection of building upgrades from a set of feasible alternatives for each building fixtures and equipment, (2) the energy and water consumption of all building fixtures and equipment, and (3) all alternatives of LEED-EB credit areas. Accordingly, the present research focuses on addressing the limitations of the existing studies and meeting the demand of building owners and operators in managing their buildings.

2 RESEARCH OBJECTIVES

The objective of this research is to develop an optimization model that is capable of maximizes the number of earned LEED-EB points within a specified upgrade budget or achieving LEED certification with minimum upgrade cost. For example, the maximum number of LEED-EB points can be identified for a facility within an upgrade budget of $80,000. Similarly, the optimization model is capable of identifying specified LEED certification, e.g. Silver level, with minimum upgrade cost. The model is developed in three steps that focus on: (1) identifying decision variables and formulating objective functions and constraints, (2) computational step to select an optimization algorithm that can identify optimal building upgrades and implement model computations, (3) evaluation step to test the model performance and demonstrate its capabilities using a case study of a rest area building located in Illinois. The goal of the developed optimization model is to enable the capability of optimizing all LEED-EB credit areas while considering available upgrade budgets, energy and water consumption of all building equipment and fixtures, and selection of building upgrade measures from a set of feasible alternatives. The outcome of this research work is expected to support decisions makers, building owners and operators, building managers, and contractors to maximize the sustainability of their buildings and achieve LEED-EB certification within limited upgrade budgets. The following sections outline the development of the model and its evaluation with the use of a case study.

3 MODEL DEVELOPMENT

The decision variables in the model are designed to represent all feasible alternatives of building upgrade measures that are capable of (1) affecting building performance in terms of energy and water, and (2) earning credit points in the LEED-EB rating system. These decision variables are grouped and organized in two major categories: (1) energy and water consumption variables, and (2) LEED-EB credit area variables. In the first category, decision variables are designed to model the selection, from a set of feasible alternatives, of green fixtures and/or equipment that affect building energy and water consumption such as combination of lighting fixtures and bulbs, motion sensors for interior-lighting, vending-machines, hand dryers, water heaters, HVAC systems, water faucets, urinals, toilets, and solar panels and inverters for grid connected photovoltaic systems. The selection of these measures has a direct impact on building energy and water consumption and accordingly they are used in the present model to calculate the number of points that can be earned in related credit areas in in the water efficiency division and the energy and atmosphere division in the LEED-EB rating system. This category was modeled with integer decision variables M_j^i, and M_{RE} which represent (1) the selection of building fixture or equipment M_j in building location i from a set of feasible alternatives, where the possible values of i depend on the number of locations of a building fixture or equipment M_j and the possible values of j depend on the type of building fixture or equipment, and (2) the percentage of renewable energy M_{RE} that can be generated at the building site. For example, M_7^6 represent the selection of a hand dryer, from a set of feasible alternatives, at location # 6 of the building.

In the second category, each decision variable represents the selection of a building fixture and/or plan, from a set of feasible alternatives, to earn the number of points in its related LEED-EB credit area. This category was modeled with integer decision variables C_{LEED}^k which represent the selection of alternative C_{LEED} in LEED-EB credit area k from a set of feasible alternatives, where k ranges from 1 to 47 to model all credit areas of the LEED-EB rating system. For example, decision variable C_{LEED}^7 represents the selection of an upgrade measure to reduce the roof heat island effect to enable earning the available one point in credit area 7.2 in the sustainable sites division in the LEED-EB rating system.

The objective functions of the optimization model are designed to calculate and minimize the building upgrade cost or calculate and maximize the number of earned LEED points. The total upgrade cost is calculated by adding up all the required upgrade costs for (1) achieving the selected LEED-EB credit areas, (2) installing selected energy and water fixtures and/or equipment such as light bulbs and water heaters, and (3) satisfying all the prerequisites of the LEED-EB rating system. The total number of LEED points is calculated by adding up the credit points that can be achieved based on the values of decisions variables in the aforementioned two groups. It should be noted that the model integrates algorithms to automatically calculate the number of LEED-EB points that the building can achieve.

In order to ensure that the developed optimization model is generating practical solutions, four constraints were integrated, including: (1) upgrade budget constraint, (2) LEED-EB prerequisite constraints, (3) building performance constraints, and (4) Photovoltaic system constraints. The upgrade budget constraint is designed to ensure that the upgrade cost of replacing building fixtures and equipment and achieving LEED credit areas is less than or equal to the available upgrade budget. The LEED-EB prerequisite constraints are integrated in the model to ensure that the generated solution meet the minimum performance requirements of the LEED rating system in fours areas of Water efficiency, energy and atmosphere, indoor environmental quality and materials and Resources. The building performance constraint is designed to ensure that the building after implementing the selected upgrade measures will satisfy all the specified levels in various building performance categories such as lighting luminance, space heating and cooling, and water heating. The photovoltaic system constraint is designed to satisfy the design requirements of the photovoltaic system.

4 Model Implementation

Once the model is formulated, the optimization algorithm is selected and model computations are performed to identify the optimal solution of the problem. The model computations are performed using Genetic Algorithms (GAs) because of their capabilities of (1) solving optimization problems that include nonlinearity in the model objective functions and constrains, (2) identifying optimal solutions for the present problem in a reasonable computational time, and (3) modeling the present problem with the least number of decision variables and constraints (Aytug and Koehler 1996; Greenhalgh and Marshall 2000; Pendharkar and Koehler 2007; Goldberg 1989).

The developed optimization model is designed to calculate electricity and water consumption of all building fixtures and equipment except HVAC systems and water heaters based on the characteristics of the energy and water devices, and their operational schedule. The energy consumption of the HVAC systems and water heaters are calculated in the model using the Quick Energy Simulation Tool (eQuest) (DOE2 2013).

The developed model integrates several databases that include feasible sustainability measures and building fixtures and equipment. These databases include product data of manufacturer and models, cost data, energy and water data, and physical characteristics for a number of building fixtures and equipment, including interior lighting fixtures and bulbs; exterior lighting fixtures and bulbs; motion sensors; hand dryers; vending machines; HVAC equipment; ground-source heat pumps; water heaters; solar panels and inverters; water coolers; PCs; and water faucets, urinals, and toilets. The model is designed to allow the model user to select the existing building fixtures and equipment from the databases where the model analyzes the replacement of these fixtures and equipment during the optimization process. The optimization model and its databases provide the flexibility of integrating new and updated sustainability measures as they become available in the market in the future.

5 CASE STUDY

In order to evaluate the performance of the developed model and demonstrate its new capabilities, a case study of an existing rest area building located in Illinois is analyzed and optimized. The rest area building is located in Illinois, consisting of two identical buildings that run along the north and south bounds of I-74. The buildings have approximately 1.5 million visitors annually and the rest area provides travel information, restrooms, vending machines, parking spaces, outdoor picnic areas, and other services to travelers. The two buildings are identical and accordingly this case study focused on only analyzing the southbound facility, with an area of 3,700 sf.

In terms of the energy consumption, the building includes interior and exterior lighting, water heaters and coolers, hand dryers, air conditioners, space heating, vending machines, and a water treatment system with an attached well pump as the facility gets its water from groundwater. The exterior lighting includes lighting poles in the parking lot as well as poles along I-74, and exterior lighting fixtures for the facility itself. The interior lighting includes lighting in the lobby, restrooms, storage room, mechanical room, vending area, and maintenance room. In the lobby and vending area, the lights must be on at all times because there are surveillance cameras to maintain safety and security of the building occupants. The facility is heated and cooled using an air handling unit, two water boilers, and two air cooled condensing units. The rest area includes six vending machines: three for drinks, two for snacks, and one for hot drinks. The southbound building also includes two ceiling fans, two electric heater units, a small refrigerator, microwave, and a computer for surveillance cameras. An electrical water heater with a capacity of 119 gals is used in the facility to provide hot water. Toilets, urinals, sinks, and faucets comprise the majority of water consumption in the facility.

An energy simulation model was created using eQuest to calculate energy consumption of the building for alternatives of the HVAC and water heaters. The data of the rest area building was fed into the optimization model to identify the optimal selection of building upgrades to achieve specified LEED certification with minimum upgrade cost or achieve the highest number of points within a specified budget, as shown in Figure 3. For example, the minimum upgrade costs that were identified to achieve a certification level of Certified, Silver, Gold, and Platinum levels are shown in Figure 3 for solutions (a), (b), (c), and (d) with $10,213, $24,968, $47,359, and $253,192 upgrade costs, respectively. The model is designed to generate detailed results for each of the identfied optimal solution wich include type and location of each building upgrade, chracteristics of the recommended upgrade measure of building fixture or equipment, and expected upgrade cost and earned number of LEED points.

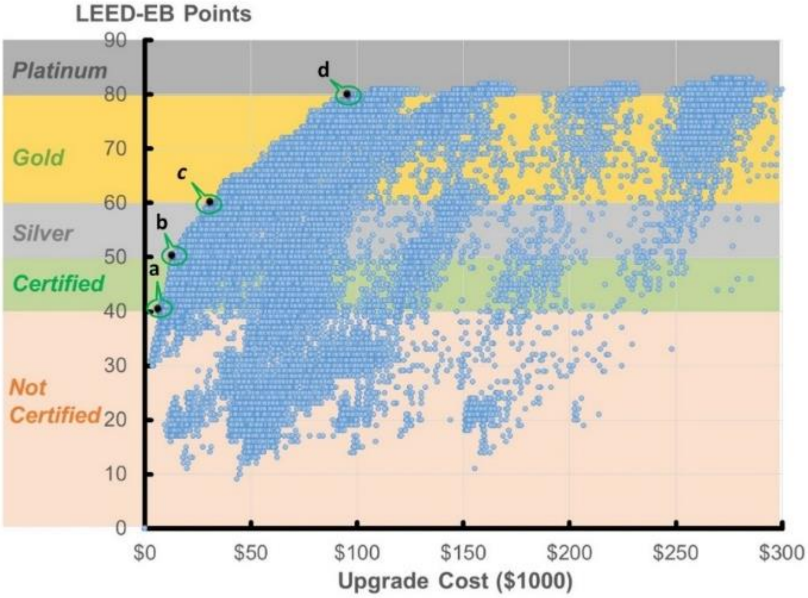

Figure 3: Model results for achieving LEED certification with minimum upgrade cost

6 SUMMARY AND CONCLUSIONS

This paper presents the development of an optimization model that is capable of identifying optimal selection of building upgrades to achieve LEED certification for existing buildings with minimum upgrade cost or achieve highest points of the LEED rating system within a specified budget. The optimization model is developed in three steps, including model formulation step that focuses on model decision variables, objective function, and constraints; computational step that focuses on selecting optimization algorithm and implementing the model calculations; and evaluation step that focuses on testing and refining the model performance. The model decision variables are designed to represent building upgrades that allow earning LEED credit points as well as building fixtures and equipment that impact energy and water consumption of buildings. The model objective functions are designed to calculate and minimize building upgrade cost or calculate and maximize the number of earned LEED points. The optimization model integrates a number of constraints to ensure the practicality of the generated solution including, upgrade cost, minimum requirements of the LEED rating system,, building performance and renewable energy design requirements.

A case study of an existing building is used to evaluate the model performance and illustrate its use. The existing building is located in Illinois with a total surface area of 3,735SF. The optimization model was able to identify the optimal solutions to achieve the different levels of the LEED rating system with minimum upgrade cost. Furthermore, the optimization model was able to generate the highest number of points for various specified budgets. The optimization model is expected to support building owners and operators to maximize the sustainability of their buildings using the LEED rating system. The capabilities of the model are limited to building upgrades that do not require significant upgrade cost such as replacing glazing and building insulation. Future expansion of the model can model additional decision variables for building envelope. Furthermore, the capabilities of the optimization model can be expanded to model additional LEED rating systems such as building design and construction, and homes.

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