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OPTIMIZING SELECTION OF BUILDING MATERIALS AND FIXTURES TO REDUCE OPERATIONAL COSTS

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Abstract: Buildings generate a considerable amount of greenhouse gases throughout their lifecycle. 80% of energy is typically consumed during the operating phase of the building lifecycle, while the construction and demolishing phases generate only 20%. Furthermore, building typically undergo a number of renovations stages during their life. This can include modifications to fixtures and equipment such as lighting fixtures and HVAC equipment; or building envelope such as windows, glazing, and wall and roof insulation. This paper presents the development of an optimization model that is capable of identifying the optimal selection of building upgrades to minimize building operational cost within a specified upgrade budget. The optimization model is expected to support building owners and their representatives in their ongoing efforts to minimize the operational cost of their buildings where renovation is planned. The optimization model is developed in four main steps. These steps include (1) Identifying decision variables that represent the desired building upgrade measures; (2) formulating objective function to minimize operational cost of existing buildings; (3) modeling all relevant constraints to ensure the practicality of the model results; and (4) implementing the model computations using Genetic Algorithms. The capabilities of the model are demonstrated using a case study of a commercial building. The results of the model showed a 42% reduction in operational costs with an upgrade budget of $125,000. Most of the operational cost savings were attributed to the installation of the photovoltaic system which saved about $2,262 in operating costs annually. The model was run with two other upgrade budgets of $75,000 and $175,000 to show the impacts of the upgrade budget on annual operating costs.

1 INTRODUCTION

Buildings generate a considerable amount of Greenhouse Gas (GHG) emissions due to significant energy and water use during operation. Commercial and industrial facilities are reported to generate 45% of the GHG emissions generated in the United States (Environmental Protection Agency 2013). The Environmental Protection Agency (EPA) estimated that if existing buildings improved efficiency by 10%, they could save $40 billion in building lifecycle costs and prevent 49 million tons of GHG emissions from releasing into the atmosphere over their lifetime. This is equivalent to eliminating emissions of 19% of registered vehicles in the United States (Energy Star, 2018). Improving the performance of existing buildings presents a challenging task and developing optimization models to help decision makers in this challenge is an urgent need. Currently, large number of building products available on the market with various characteristics, which contributes to the challenging task of identifying optimal building products that provide the best energy and water performance.

Eighty percent of the total energy consumption of buildings is consumed throughout the buildings life while only twenty percent is consumed during construction and demolition (WBCSD 2009). This highlights the importance of reducing the energy consumption of building operation to minimize the negative environmental impacts of buildings. Additionally, building owners seek to adopt building upgrades that reduce operational costs and provide reasonable payback. Furthermore, energy cost savings are correlated to improved net operating income among tenants in additions to energy savings (Appraisal Institute 2013). Owners benefit since commercial buildings that are Energy Star and LEED-certified buildings can generate higher lease rates and selling prices (Kok, Mcgraw, and Quigley 2016).

Improvement of the thermal envelope of an existing building increases energy efficiency over the lifecycle of the building. Upgrading envelope of existing buildings have been shown to be effective in reducing energy costs and lowering environmental impacts by up to 29% (Kim & Park, 2017). Studies demonstrate that different insulation strategies can be effective for improving energy efficiency in different climates (Pulselli, Simoncini, and Marchettini 2009; Aditya et al. 2017).

While replacing building envelope materials and HVAC equipment can improve energy performance, there are huge number of building products on market to select from. In addition, several factors affect the selection process such as budget and performance constraints. Using tools to help with the selection of materials and equipment is important to facilitate the selection process. Optimization models have used to support decision makers to identify optimal selection of building upgrades that meet their project goals such as energy efficiency and conservation. For example, an optimization model was developed to identify the optimal selection of building upgrades to achieve LEED certification for existing buildings with minimum upgrade cost (Abdallah, El-Rayes, & Liu, 2016). The model is designed to identify a set of building upgrades that are able to achieve specified LEED certification level, such as Silver, with minimum upgrade cost (Abdallah, El-Rayes, & Liu, 2016). Another study was conducted to identify optimal selection of building upgrades to minimize negative environmental impacts of existing buildings within specified upgrade budget (Abdallah & El-Rayes, 2015).

Several studies have explored optimizing building envelopes materials such as wall insulation and exterior cladding and glazing for improvements in energy performance. Güçyeter et al. have evaluated different envelope retrofit strategies through a calibrated simulation approach to minimize the annual energy consumption of buildings (Güçyeter and Günaydin 2012). Similarly, Asadi et al developed a multi-objective optimization model to assist stakeholders in the definition of intervention measures aimed at minimizing the energy use in the building while satisfying the occupant needs and requirements (Asadi et al. 2012). These studies have integrated optimization strategies with energy simulation modeling to improve the materials used to retrofit building envelopes.

Other research studies have used different types of evolutionary algorithms to solve problems relating to material and equipment selection and to help owners, builders and designers make key decisions on design and construction preferences (Kusiak, Tang, and Xu 2011; Wright, Loosemore, and Farmani 2002; Asadi et al. 2012). Furthermore, several research studies have focused on developing decision support models for retrofitting buildings with the aim of LEED credit improvement (Stegall and Dzombak 2004; Choi et al. 2015; Subhi, Galal, and Alkass 2014).

Genetic algorithms have been used extensively in the construction industry to support decision makers for optimization of energy performance and life-cycle costs of buildings. For Instance, one study developed an optimization model to place and size windows to improve the energy efficiency of office buildings (Caldas and Norford 2002). Another study focused on developing an optimization model capable of identifying optimal building shape to minimize lifecycle cost and energy consumption of buildings. The study showed that rectangular and trapezoidal buildings have the lowest life-cycle costs and energy performance characteristics as compared to buildings that have H-, T-, and U-shape (Tuhus-dubrow and Krarti 2010). Genetic algorithms were used in another study to help reduce the operational cost of buildings. The model was able to successfully identify building upgrade measures that are capable of reducing energy, water, and maintenance costs within specified upgrade budget (Abdallah, El-Rayes, & Clevenger, 2015).

Despite the significant contribution of the existing research studies to identify optimal selection of building upgrades within specified upgrade budgets, previous research did not consider decision variables pertaining to building envelope within limited upgrade budgets. Specifically, there is limited research that optimizes both building equipment and envelope to minimize operational costs. While energy savings is a valuable metric, it must be financially feasible for building owners. Maintenance costs and payback periods must be taken into consideration when looking at energy savings. This study focuses on addressing the limitation of existing studies by expanding the capabilities of existing models to analyze alternatives of building envelope as well as building fixtures and equipment.

2 OBJECTIVE

The primary object of this study is to develop an optimization model that is capable of identifying building upgrades to minimize operational costs within specified upgrade budgets. The optimization model is expected to support building owners and operators in their ongoing efforts to minimize building operational costs when building renovation is planned. The optimization model is developed in four main steps. These steps include (1) Identifying decision variables that represent the desired building upgrade measures; (2) formulating objective function to minimize operational cost of existing buildings; (3) modeling all relevant constraints to ensure the practicality of the model results; and (4) implementing the model computations using GA. The performance of the optimization model is tested and verified using an application example of a commercial building in Denver with various upgrade budgets. The development steps of the optimization model along with the application example are discussed in details in the following sections.

3 MODEL DEVELOPMENT

Building upgrade measures that impact energy and water consumption of existing buildings are modeled using decision variables. Decision variables are grouped in three categories of building upgrades, including (1) building energy fixtures and equipment such as lighting fixtures and bulbs, HVAC equipment, water heaters, and components of grid-connected photovoltaic systems; (2) building water fixtures such as water faucets and toilets; and (3) building envelope materials such as wall and roof insulation, and glazing.

The objective function of the optimization model is formulated to minimize building operational costs by replacing existing fixtures and equipment with more energy and/or water efficient ones, replacing materials of building envelope with better building insulation or glazing and installing grid-connected photovoltaic systems. The model is designed to calculate building operational costs based on energy and water consumption. The model is designed to calculate the building energy consumption using Quick energy simulation software (eQuest) based on the characteristics of the building such as location, building orientation, construction materials, insulation and glazing type, and building schedule; and building fixtures and equipment such as lighting fixtures, HVAC equipment, and water heater.

Several constraints were integrated in the model to ensure that the generated solutions are practical, including upgrade budget, assembly constraints, building performance constraints, and photovoltaic system constraint. The optimization model integrates a constraint to ensure that the recommended building upgrades do not exceed the specified upgrade budget. The model calculates the total building upgrade cost based on the recommended replacement of building fixtures and equipment, installation of more efficient building insulation or glazing, and installation of the grid-connected photovoltaic system. Another set of constraints were integrated in the model to maintain building functionality. These constraints ensure that the building is able to adequately operate for occupant usage and not negatively impact the comfort of the occupants. Areas of building functionality with regard to light luminance, space heating and cooling as well as water heating were modeled using constraints to meet minimum operating standards. Fixtures and equipment alternatives such as HVAC equipment, water heaters; and lighting fixtures are required to be performing within a specified range to meet building performance standards. If an alternative did not fall within the specified range, the optimization model will not recommend its use. For example, if a light fixture alternative will reduce the light lumens output by more than a specified percentage (ex. 5% of the existing light output in the space), the optimization model will not recommend it. Similarly, HVAC and water heater equipment are replaced in the model with similar ones that satisfy the existing building performance. Furthermore, the photovoltaic system constraints were designed to ensure that the model is meeting the design requirements of the grid-connected photovoltaic (PV) system. A number of constraints were formulated to ensure that the capacity of the grid-connected PV system exceeds the specified energy demand, the number of inverters and solar panels are optimized to meet the design requirements, and the required space of the PV system meets the available space at the building.

The implementation of the developed optimization model was performed in two steps: (1) creating databases for building fixtures, equipment, components of renewable energy systems, insulation materials, and glazing types; and (2) executing optimization model computations using genetic algorithms;

The developed optimization model integrates several databases that include products of building fixtures, equipment, components of renewable energy systems, wall and roof insulation, and glazing types. These databases include general product data, cost data, energy and water characteristics data, and physical characteristics for alternatives of exterior lighting fixtures and bulbs, interior lighting fixtures and bulbs, motion sensors, HVAC equipment, water heaters, wall insulation, roof insulation, glazing types, solar panels, solar inverters, water faucets, and toilets. The products of building fixtures and equipment and their costs in the integrated databases are collected from manufacturers and retailers online source. The installation costs of these building fixtures and equipment were calculated using RS Means building construction cost data (RSMeans 2013; Plotner et al. 2016).

The computations of the optimization model are executed using Genetic Algorithms (GAs) due to their capabilities of modeling the non-linearity and step changes in the objective function and constraints and identifying the optimal solutions in reasonable time and effort. The model is designed to perform (i) replacements of building fixtures and equipment with more energy and water efficient ones, (ii) replacements of existing insulation and glazing with more energy efficient alternatives, and (iii) installations of the grid-connected PV system. The solution process starts by searching for feasible replacements of HVAC equipment and water heaters from an integrated database in the model. This process searches for and extracts all possible alternatives of HVAC equipment and water heaters from the database that have capacities within a specified range of 80% to 120% of the existing capacities of the building equipment. After identifying those feasible replacements, input files are generated automatically by the developed optimization model for eQuest based on the identified practical alternatives for HVAC systems and water heaters. eQuest is used to run all input files to calculate the energy consumption of the building for feasible replacements, which are then stored in a database where the HVAC alternative can be recalled and used during the optimization process. The GA computations in the model start by generating a population of random solutions by replacing all the existing fixtures and equipment, insulation, glazing with feasible alternatives from the model databases as well as installing grid-connected PV systems. The fitness of these solutions is evaluated based on the building operation cost and model constraints. Solutions that satisfy all the model constraints that achieve low building operational cost are identified as solutions with high fitness values.

4 APPLICATION EXAMPLE

A building located in Highlands Ranch, CO was selected to evaluate the model performance and illustrate its capabilities. The building was originally constructed to house three separate businesses for multi-use assemblies. At the time of the study, only two of the units had been built out with the middle unit standing vacant. Construction on the building began in December 2016 and a certificate of occupancy for the first unit was issued in September 2017. The building has a total area of approximately 7,140 square feet with the annual operating cost of $13,645, consisting of exercise area, lobby, office, restroom, mechanical & electrical room. The major contributors of the building operational costs include interior and exterior lighting, space heating and cooling, water heating, water faucets, urinals, and toilets. Equipment loads were comprised of an electric water heater, two water fountain/ cooler units, two sound systems, and 15 treadmills.

Table 1 shows a sample of the input data for building fixtures and equipment of the existing public building example.

Table 1: Building Equipment and Fixture Input Data

Building Fixtures	Quantity	Working Hours per Day	Light output (lumens)	Allowed Reduction in Lighting Intensity (% of the unit)
High output bulb with Medium (E26) socket w/ T2 Bulbs. 9-13 Watts	53	15	1490 Lumens 1000 Lumens 850 Lumens 650 Lumens 600 Lumens	5% (lumens)
Bulb with GX24q-3 socket w/ T4 Bulbs 26-32 Watts	44	15	2200 Lumens 1800 Lumens	5% (lumens)
Longitudinal fluorescent lamp, 4 feet with bi-pin socket	8	24	2950 Lumens	5% (lumens)
HVAC System - (1) RTU 7.5 Ton Cooling and 184 Kbtu heating capacity; (3) 8.5 Ton Cooling and 220 220 Kbtu heating Capacity	4	24		0%
Water heater with a capacity of 80 gallons	1	24		0%
K-13461 0.5 GPM Faucet	4	Per Use		0%
1.6 GPF Toilet	4	Per Use		0%

To perform the optimization analysis for the case study, an energy simulation model was created. eQuest 3-65 energy simulation software was used for this study due to its user-friendly interface, short computation time, and ability to model different energy inputs for simulation. As-built construction drawings for the envelope and interior spaces were used to model the building. Project submittals were also used to create accurate building assemblies for baseline modeling data and assumptions. Inputs such as location, geometry, number of rooms, occupancy, and operating schedule were input into eQuest. Additionally, HVAC thermal zones were created to help isolate the energy output for various spaces in the model. Spaces in eQuest were then divided into their respective activity so that energy loads could be easily assigned.

After creating the energy simulation model, it was calibrated according to the existing energy simulation bills. Different scenarios for the combination of HVAC and insulation options underwent simulations to determine an optimal HVAC combination for the specified scenario. The simulation process integrated eQuest model and then generated an additional eQuest file with different HVAC systems. Each new eQuest model generated both energy and gas data for a 12 month period and the simulation output was recorded in the optimization model database. Finally, input data was fed into the optimization model to identify optimal selection of building upgrades within a specified upgrade budget.

Three different budgets of $75,000; $125,000; and $175,000 were used as budget limits to identify the optimal building upgrades. The optimal solutions based on the three upgrade budget scenarios of $75,000, $125,000 and $175,000 led to total cost of $67,887, $118,703 and $148,925 respectively. The upgrade budget of $175,000 had the lowest annual operating cost of $7,378. It had the second lowest annual energy and water consumption cost of $4,338 but the lowest maintenance cost of $3,027. The upgrade budget of $125,000 had the second lowest annual operating cost at $7,985 however it generated the lowest annual energy and water consumption cost of $3,887. The upgrade budget of $75,000 had the highest annual operating cost of $8,102. Table 2 shows the detail of optimal upgrade costs per category for each of the budgets of $75,000, $125,000 and $175,000.

Table 2: Upgrade Costs for each budget Scenario

Upgrade Budget (USD)	Category	Upgrade Costs (USD)
$75,000	Interior Lighting	160
	Motion Sensors	1,142
	HVAC System, Wall & Roof Insulation, Glazing	10,000
	Water Heater	7,065
	Photovoltaic System	47,428
	Bathroom Faucets	479
	Bathroom Toilets	1,613
	Total	67,887
$125,000	Interior Lighting	341
	Motion Sensors	1,051
	HVAC System, Wall & Roof Insulation, Glazing	40,000
	Water Heater	7,036
	Photovoltaic System	67,426
	Bathroom Faucets	739
	Bathroom Toilets	2,110
	Total	118,703
$175,000	Interior Lighting	1,166
	Motion Sensors	1,166
	HVAC System, Wall & Roof Insulation, Glazing	76,800
	Water Heater	7,065
	Photovoltaic System	60,557
	Bathroom Faucets	495
	Bathroom Toilets	1,676
	Total	148,925

The annual operational cost savings for each of the budgets of $75,000, $125,000 and $175,000 were identified as $5,291, $5,408, and $4,945 respectively. The operating costs for all scenarios improved significantly from the initial renovation project which had an annual operating cost of $13,645. All three of the budget scenarios that ran were able to improve on the baseline operational cost. The $175,000 budget was able to reduce operational costs by 46% from the original renovation while the $75,000 budget and $125,000 budget reduced operational costs by 41% and 42%, respectively. Most of the savings were directly related to energy cost savings as the $125,000 budget improved energy costs from $9,295 to $3,887. The energy cost for the $175,000 budget went from $9295 to $4350 while the $75,000 budget went from $9295 to $4004.

5 SUMMARY AND CONCLUSION

This paper presented the development of an optimization model to identify the optimal selection of building upgrades to minimize the operational cost of buildings while complying with a specified upgrade budget. The optimization model was developed in four main steps: (1) Identifying decision variables that represent the desired building upgrade measures; (2) formulating objective function to minimize operational cost of existing buildings; (3) modeling all relevant constraints to ensure the practicality of the model results; and

(4) implementing the model computations using GAs. The optimisation results can be used to provide recommendations to building owners and operations on how to reduce annual operating cost by replacing specific fixtures and equipment.

This model was tested on a building in Highlands Ranch, Colorado to demonstrate the model capabilities in the commercial construction sector. The model was able to identify which sustainability measures could be used to reduce operating costs. Additionally, it showed how the building envelope upgrades can impact the operational performance of a building. While this study focused on existing buildings, further research could be done to identify how similar models could impact the construction and preconstruction phases to deliver more sustainable upgrades to initial building designs in order to reduce to building operating cost. This model can identify small upgrade changes to building materials and fixtures that can improve the performance of buildings without the need for a significant design changes. Using this model could help all key decision makers have a competitive advantage during the construction process which could help improve the building lifecycle costs.

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