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OPTIMIZING BUILDING UPGRADES TO MINIMIZE ENERGY AND WATER CONSUMPTION

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Building sector in the United States is responsible for 41% of energy consumption, 73% of electricity consumption, and 14% of water consumption. Energy and water consumption of buildings can be significantly reduced by identifying and implementing green building upgrade measures based on available budgets especially in aging buildings which represent 70% of existing buildings in the United States. This paper presents the development of an optimization model that is capable of identifying the optimal selection of building upgrade measures to minimize energy and water consumption of existing buildings while complying with limited upgrade budgets and building operational performance requirements. This optimization model is designed to estimate building energy consumption using energy simulation software packages, is integrated with databases of building products, and performs analysis of replacing existing building fixtures/equipment and installing renewable energy systems during optimization computations to identify the replacement of building products that minimizes energy and water consumption. The model is designed to provide detailed results for building owners, which include specifications for the recommended upgrade measures and their location in the building; required upgrade cost; expected energy and water, operational, and life-cycle cost savings; and expected payback period.

Keywords: Existing Buildings, Upgrade Measures, Limited Budget.

1 INTRODUCTION

Buildings in the United States are responsible for significant negative environmental impacts due to high percentage of energy, electricity, and water consumption of 39%, 72%, and 14% respectively (U.S. EPA 2009). These environmental impacts can be reduced by implementing a number of sustainable measures such as energy efficient building fixtures and equipment, renewable energy systems, and water-saving plumbing fixtures. The implementation of these sustainable measures always results in high upgrade costs, and decision makers are often faced with the challenge of selecting building upgrade measures that comply with their upgrade budget and achieve the highest reduction in energy and water consumption. To support building renovation, a pressing need exists to develop an optimization model that is capable of identifying the selection of building upgrade measures to minimize energy and water consumption while complying with available upgrade budgets.

Several studies exist that focus on evaluating the implementation of sustainability measures on energy and water consumption of buildings, including energy-efficient lighting systems (Henderson 2009), motion sensors to control lighting systems in commercial buildings (VonNeida *et al.* 2001), energy efficient HVAC systems in new and existing buildings (Das et al. 2013), renewable energy systems (NREL 2001), and water saving plumbing fixtures (GAO 2000). Furthermore, several optimization models have been developed to minimize negative environmental impacts and operational costs of existing buildings (Abdallah and El-Rayes; Abdallah et al. 2014), identify optimal selection of structural and architecture design of new buildings (Fialho et al. 2011), and identify optimal decisions of building renovations (Juan et al. 2010).

Despite the significant contribution of the existing research studies, there are none or only limited models that are capable of identifying the optimal selection of building sustainability measures to minimize energy and water consumption. Furthermore, there are no or limited models in the literature that cover various sustainability measures of building fixtures and equipment, and renewable energy systems to minimize energy and water consumption of existing buildings while complying with available upgrade budgets and specified building operational performance.

2 RESEARCH OBJECTIVE

This paper focuses on developing an optimization model that is capable of minimizing energy and water consumption of existing buildings by installing efficient building fixtures and equipment, and renewable energy systems that comply with available upgrade budgets. The optimization model is developed in three main phases (1) model formulation phase which include the identification of model decision variables and formulation of the model objective function and constrains, (2) model implementation phase which include the computations of the model using Genetic Algorithms, (3) evaluation phase which include the validation of the model performance and illustration of its capabilities using a case study of an existing building.

3 MODEL FORMULATION PHASE

Energy is consumed in buildings mainly by fixtures and equipment in the various building systems such as lighting, heating ventilation and air conditioning, and water heating. In addition, plumbing fixtures are responsible for the majority of water consumption in buildings such as water faucets, showerheads, kitchen sinks, urinals, and toilets. The developed optimization model is designed to minimize energy and water consumption of buildings by replacing existing building fixtures and equipment with more energy- and water- efficient units and installing renewable energy systems to offset energy demands such as photovoltaic systems. The developed optimization model calculates energy consumption of buildings using energy simulation software packages such as QUick Energy Simulation Tool "eQUEST" (USDOE 2013). The model is also designed to calculate water consumption in buildings based on type of building, type of plumbing fixtures, and number of occupants according the guidelines of the LEED rating system for existing buildings (USGBC 2014).

The decision variables are designed to model all feasible alternatives of building fixtures and equipment that consume energy or water, including HVAC equipment, light fixtures and bulbs, water heaters, hand dryers, refrigerators, vending machines, water faucets, urinals, and toilets. Furthermore, other decision variables are used to model the selection of installing motion sensors, components of photovoltaic systems such as solar panels and inverters, and percentage of renewable energy that can be generated at the building site. The decision variables of building fixtures and equipment and components of renewable energy systems are modeled using integer decision variables where integers represent IDs from integrated databases of building products. The percentage of renewable energy is modeled using integer decision variable with a lower limit of 0% and specified upper limit such as 30%.

The objective function of this optimization model is designed to minimize energy and water consumption of existing buildings. The model combines the energy and water consumption of buildings using Building Energy and Water Performance Index (BEWPI). The value of this index ranges from 0.0 which represent a fully sustainable building with net zero energy and zero water consumption to 1.0 which represent no reduction in the building energy and water consumption, as shown in Eq. (1).

$$BEWPI = \frac{BTU^R}{BTU^e} * W_{EC} + * \frac{BWC^R}{BWC^e} * W_{WC} \quad (1)$$

where BEWPI is Building Energy and Water Performance Index; BTU^R is building energy consumption in British thermal units (BTUs) after implementing upgrade measures; BTU^e is existing building energy consumption in BTUs; BWC^R is building water consumption after upgrade measures; BWC^e is existing building water consumption; and $W_{EC}, and\, W_{WC}$ are relative importance weights of energy consumption and water consumption, respectively.

The optimization model integrates a number of constrains to ensure its practicality, including building performance constraints and upgrade budget constraint. The building performance constraints are designed to ensure that specified operational performance levels of the building will be maintained after implementing the recommended fixtures and equipment, including light levels, space heating and cooling, and water heating capacity. The upgrade budget constraint is designed to ensure that the cost of upgrading the building fixtures and equipment and installing renewable energy systems will not exceed the specified upgrade budget.

4 MODEL IMPLEMENTATION PHASE

The developed model is designed to execute the optimization computations using Genetic Algorithms (GAs) due to its capability of modeling the optimization problem with the least number of decision variables, modeling non-linearity in the objective function and constraints of the model, and identifying optimal solutions in reasonable computational time and effort (Goldberg 1989; Pendharkar and Koehler 2007).

The developed model is designed to start the computations by searching integrated databases to identify feasible replacements of the existing HVAC equipment and water heaters. The model then creates input files for eQuest to calculate energy consumption of the various feasible alternatives. The calculated energy consumption of the various alternatives of HVAC and water heater equipment are stored in the integrated databases. The GA computations then starts by generating random selection of building upgrade measures which represent the initial population. The fitness of this initial population is evaluated based on the value of the Building Energy and Water Performance Index (BEWPI) and the model constraints. The solutions that satisfy all the constraints and achieve low values of BEWPI are identified as solutions with high fitness values. On the other hand, solutions that achieve high values of BEWPI or do not satisfy the model constraints are identified as solutions with low fitness values or infeasible solutions, respectively. Solutions with high fitness are then ranked based on their index of BEWPI where the GA operators of selection, crossover, and mutation are applied to generate a new set of population. This process is repeated until no further improvements are achieved within a predefined number of iterations (Reed *et al.* 2000).

The developed optimization model is integrated with databases of building fixtures and equipment, components of renewable energy systems which include general product data, energy and water characteristics, cost data, and physical characteristics. These integrated databases include light bulbs and fixtures, HVAC equipment, motion sensors, water heaters, hand dryers, vending machines, refrigerators, water coolers, solar panels, solar inverters, water faucets, urinals, and toilets.

5 EVALUATION PHASE

An existing building is used to analyze the performance of the developed optimization model in minimizing energy and water consumption. This building is located in Illinois and it was selected due to its high energy and water consumption and its continuous operation. This building was built in 1989 and renovated in 1992 with a surface area of 2,500 square feet. The building includes men's and women's bathrooms, travel information desk, lobby, vending area, storage rooms, mechanical room, attic, and detached small garage. It also has parking lot that can accommodate visitors with cars and semi-trucks. The major contributors of energy and water consumption include interior and exterior light fixtures, HVAC systems, water heater, six vending machines, five water coolers, and four hand dryers. The major contributors of water consumption in the building include six water faucets, eight toilets, and two urinals.

To minimize energy and water consumption of the aforementioned building using the developed optimization model, the model requires input data of (1) building characteristics such as size, construction materials, air infiltration, doors and windows, operational schedule, allocation of building activities, and airflow; (2) building equipment and fixture characteristics which can be selected from the model databases; and (3) importance weights of BEWPI which were specified as 75% and 25% for energy and water consumption, respectively. It should be noted that the importance weights of the BEWPI can vary from one decision maker to another, and accordingly the model enables them to specify their own weights.

The developed optimization model was used to minimize the energy and water consumption of the building with various upgrade budgets that ranged from $25K to $100K. The model was able to identify the optimal upgrade decisions for all the specified upgrade budgets, as shown in Figure 1. For example, solution (a) in Figure 1 identified by the model as an optimal solution for an upgrade budget of $50K, and it provides a moderate reduction in the building energy and water consumption index of (BEWPI = 0.673) with an upgrade cost of $49,572. On the other hand, solution (b) is identified by the model as an optimal solution for an upgrade budget of $100K, and it provides minimum index of (BEWPI = 0.578) that caused reduction in energy consumption to 67% and water consumption to 31%, as shown in Figure 1.

The developed optimization model is designed to generate action reports for the generated optimal solutions that include detailed information of all the recommended building upgrade measures. The model is also designed to generate results on the building operational costs, life-cycle cost, and energy and water consumption before and after implementing the recommended upgrade measures. The results of the model identify the optimal selection of building upgrades based on an identified upgrade budget which support building owners and operators in their ongoing task of maximizing the sustainability of their building.

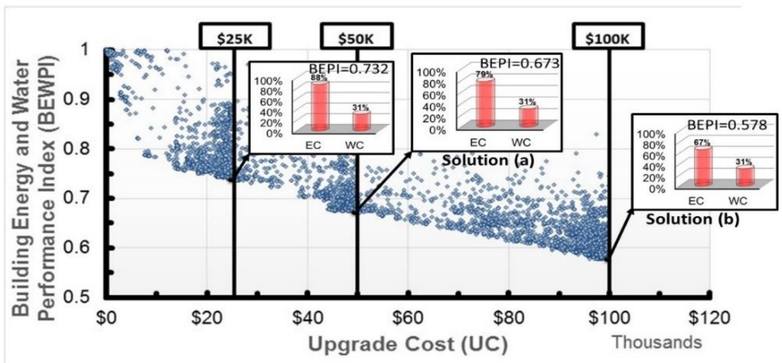

Figure 1. Results of minimizing negative environmental impacts of the rest area.

6 SUMMARY AND CONCLUSIONS

This paper presents an optimization model that is capable of minimizing energy and water consumption of existing buildings by replacing existing building fixtures and equipment with more energy- and water- efficient units and installing renewable energy systems such as photovoltaic systems. The model is designed to include decision variables of building fixtures and equipment, energy saving measures such as motion sensors, components of renewable energy systems, and percentage of renewable energy. The objective function is designed to combine the energy and water consumption in one index that ranges from 0.0 to 1.0 where the optimization model minimizes the value of this index during the optimization computations. The model is integrated with a number of constraints to identify feasible solutions that do not exceed a specified upgrade budget and to maintain specified building performance levels of lighting, heating and cooling, and water heating.

The implementation phase of the model includes the creation of integrated databases that include products of building fixtures and equipment and component of renewable energy systems to facilitate input and output data of the model. This phase also includes the execution of the model computation using GAs due to its capability of dealing with the present optimization problem in reasonable computational time and effort. The evaluation phase validates the model performance to identify the optimal selection of building upgrade measures for various budgets. The model is designed to provide detailed results for the identified optimal solutions which include details of the recommended building fixtures and equipment, location in the building, upgrade cost, expected reduction in energy and water consumption and payback period. The new capabilities of the present model provide support to building owners and operators in their ongoing efforts to minimize building energy and water consumption of existing buildings. Future expansion of the model is needed to include other analyses of the building envelope such as type of insulation, windows, and doors to reduce energy consumption, especially where energy consumption is dominated by HVAC systems.

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