Building and Environment 115 (2017) 118–129

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

# An optimization framework for building energy retrofits decision-making

Amirhosein Jafari*, Vanessa Valentin

*Department of Civil Engineering, University of New Mexico, MSC01 1070, Albuquerque, NM, 87131, United States*

ARTICLE INFO

*Article history:*
Received 25 October 2016
Received in revised form
13 January 2017
Accepted 17 January 2017
Available online 19 January 2017

*Keywords:*
Energy retrofits
Decision-making
Life-cycle cost
Optimization model
Residential building

ABSTRACT

Buildings are major consumers of energy in the United States. One way to improve building's energy efficiency is through energy retrofitting. The selection of a combination of retrofitting measures for a specific building is a complex process. Despite of the numerous resources that provide advice on how to retrofit a facility, the study of important variables affecting this decision remains limited. Further research is needed on the development of decision-making models to select the optimum energy retrofitting strategy in order to maximize energy retrofitting benefits. This study proposes a decision-making framework that: (1) calculates the economic benefits of energy retrofitting in terms of reduction of life-cycle cost for a specific building during its service life; (2) determines the optimum retrofitting budget that minimizes the total life-cycle cost of the building during its service-life; and (3) selects the optimum energy retrofitting strategy (among available energy retrofitting measures) to maximize the homeowner economic benefits during service-life of the building based on available investments. This study contributes to the body of knowledge in three aspects: (1) considering a comprehensive economic objective for decision-making in energy retrofits that includes majority of cost-related components of building life-cycle cost; (2) introducing a novel simplified energy prediction method by integrating dynamic and static modeling; and (3) incorporating energy retrofitting decision-making uncertainties to reach more accurate results. In order to demonstrate the implementation of the framework, a case study exercise of a house built in 1960's in Albuquerque, New Mexico is used.


## 1. Introduction

Buildings, particularly residential buildings, are major consumers of energy worldwide. In the United States (U.S.), buildings accounted for 39% of total energy consumption and 72% of total electricity consumption, where residential buildings accounted for more than half of the total [1]. Based on the American Housing Survey by the U.S. Census Bureau [2], over 60% of the U.S. housing inventory is more than 30 years old and energy inefficient. Therefore, it is essential to target the existing building stock for energy efficient interventions as a key to substantially reduce the adverse impacts of buildings on the environment and economy [3]. The most feasible and cost-effective method to improve building energy efficiency is "energy retrofitting" [4,5]. An energy retrofit is the physical or operational change in a building itself, its energy-consuming equipment, or its occupants' behavior to reduce the amount of energy needed and convert the building to a lower energy facility.

Various energy retrofitting measures can improve building energy efficiency in different levels. These measures can be categorized in five main groups as follows [6–9]:

- *Controlling measures*: provide appropriate controls and monitors for the mechanical systems, lighting, ventilation, and the efficient use of multi-functional equipment, among others.
- *Load reduction measures*: upgrade the mechanical systems; replace fixtures, appliances, and lighting with energy efficient models, among others.
- *Enveloping measures*: insulate and air-seal the roof or ceiling, walls, and floor; replace the windows and doors with energy-efficient models.
- *Renewable energy technologies*: provide renewable-energy sources such as solar thermal systems, solar photovoltaic/thermal systems, geothermal power systems, among others.

* Corresponding author.
*E-mail addresses:* jafari@unm.edu (A. Jafari), vv@unm.edu (V. Valentin).

http://dx.doi.org/10.1016/j.buildenv.2017.01.020
0360-1323/

**Notation**

$AC$ air conditioning energy consumption zone
$AE$ appliance and electric devices energy consumption zone
$AEC$ estimated annual energy consumption cost of the building in the first year
$AEC_0$ annual energy consumption of the building before energy retrofit implementation
$AMC_i$ annual maintenance cost of implementation of $i^{th}$ activity
$Area$ Floor area of the building in square meter
$C_{Ii}$ estimated cost of implementation of $i^{th}$ retrofitting measure
$C_{SHi}$ impact of $i^{th}$ activity from CR group on building space heating energy consumption zone
$C_{WHi}$ impact of $i^{th}$ activity from CR group on building water heating energy consumption zone
$C_{AEi}$ impact of $i^{th}$ activity from CR group on building appliance and electric device energy consumption zone
$C_{LIi}$ impact of $i^{th}$ activity from CR group on building lighting energy consumption zone
$C_{ACi}$ impact of $i^{th}$ activity from CR group on building air conditioning energy consumption zone
$C_{Ej}$ amount of electricity-equivalent energy can be produced per year by $j^{th}$ activity from EP group
$C_{Gj}$ amount of gas-equivalent energy can be produced per year by $j^{th}$ activity from EP group
$C_{MRi}$ maintenance and replacement cost of $i^{th}$ activity after its MR period
$CR$ consumption-reducing measures
$d$ interest rate
$E_{AC}$ electricity consumption of the building for air conditioning before retrofitting
$E_{AE}$ electricity consumption of the building for appliance and electric devices before retrofitting
$E_{LI}$ electricity consumption of the building for lighting before retrofitting
$E_{SH}$ electricity consumption of the building for space heating before retrofitting
$E_{WH}$ electricity consumption of the building for water heating before retrofitting
$EP$ energy-producing measures
$EC$ energy consumption cost
$EL$ annual electricity consumption of the building in the first year
$FC$ future cost
$G_{AC}$ natural gas consumption of the building for air conditioning before retrofitting
$G_{AE}$ natural gas consumption of the building for appliance and electric devices before retrofitting
$G_{LI}$ natural gas consumption of the building for lighting before retrofitting
$G_{SH}$ natural gas consumption of the building for space heating before retrofitting
$G_{WH}$ natural gas consumption of the building for water heating before retrofitting
$IC$ initial investment cost
$k$ annual rate of energy cost increase
$LB$ limited budget
$LCC$ total life-cycle cost
$LCCA$ life-cycle cost analysis
$LI$ lighting energy consumption zone
$MR$ maintenance and replacement cost
$m$ number of selected retrofitting measures
$M_{MRi}$ number of maintenance and replacements need to be done for $i^{th}$ activity during service life of the building
$n$ service life of the building
$n_{CR}$ number of consumption-reducing activities
$n_{EP}$ number of energy-producing activities
$n_{MRi}$ maintenance and replacement period for $i^{th}$ activity
$NG$ annual natural gas consumption of the building in the first year
$PV_{EC}$ present value of energy consumption cost of the building during its service life
$PV_{MR}$ present value of maintenance and replacement cost of the building during its service life
$PV_{RV}$ present value of benefits from resaling the building after its service life
$PV_{TX}$ present value of property tax of the building during its service life
$RB$ rebound effect of energy efficiency
$RV$ benefits from resaling of the building
$SH$ space heating energy consumption zone
$TI$ tax credits due energy retrofits
$TX$ property tax
$U_{EL}$ electricity unit price in the first year
$U_{NG}$ natural gas unit price in the first year
$V$ resale value of the building
$V_0$ resale value of the building with no energy retrofit implementation
$WH$ water heating energy consumption zone
$x_i$ decision variable of existence of $i^{th}$ retrofitting measure to be in the best retrofitting strategy

- Human behavior: Alter energy consumption patterns of occupants by different methods such as individual metering.

The selection of a combination of retrofitting measures (called "retrofitting strategy") for a specific building is a complex process. Despite of the numerous resources that provide advice on how to retrofit a facility, the study of important variables affecting this decision remains limited. The selection process of a retrofitting strategy is a trade-off between the capital investment (the investment required to implement that retrofitting strategy) and the benefits obtained from energy retrofitting [9]. These energy retrofitting benefits can be economic (e.g., reducing operating costs), environmental (e.g. reducing air emissions), or social (e.g. enhancing occupant's comfort and health) [10]. Further research is needed on the development of decision-making models to select the optimum energy retrofitting strategy in order to maximize energy retrofitting benefits (including economic, environmental, and social). It is essential for these models to answer basic decision-making questions: what is the best amount of investment required for retrofitting a specific building? and which retrofitting measures should be implemented (as the best retrofitting strategy) to maximize the retrofitting benefits based on the available budget?