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A multiple objective optimisation model for building energy efficiency investment decision☆

Esrom Mahlatsi Malatji, Jiangfeng Zhang*, Xiaohua Xia

Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa

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ABSTRACT

A multiple objective optimisation model is formulated to help decision makers to make an optimal decision when investing in energy-efficient building retrofitting. The objectives are to maximise the energy savings and minimise the payback period for a given fixed initial investment. The model is formulated as a multi-objective optimisation problem with the net present value (NPV), initial investment, energy target and payback period as constraints and it is solved using genetic algorithms (GAs). The optimal decision is reached by choosing the most optimal actions during energy retrofit in buildings. The model is applied to a case study of a building with 25 facilities that can be retrofitted that illustrates the potential of high energy savings and short payback periods. The sensitivity analysis is also performed by analysing the influence of the auditing error of the facilities, wrongly specified energy savings, the initial investment, changes in interest rate and the changes of electricity prices on the payback period, the maximum energy saved and NPV of the investment. The outcome of this analysis proves that the model is robust.

1. Introduction

The current energy shortage around the world is the reason that energy efficiency is a subject of interest today. The most viable option to counteract this problem is by reducing the current energy consumption. With buildings consuming around 40% of the world's total energy [1], it would be beneficial to invest in building energy efficiency retrofit projects. In order to improve the energy efficiency of buildings, inefficient facilities are often replaced by highly advanced energy efficient ones. A whole range of facilities can be retrofitted if there is unlimited funding, although usually this is not the case. Nevertheless the following are some of the retrofit actions that can be taken [2–4]:

- Building improvements – insulating the roof, replacing the single glazing windows with double glazing windows and installing solar shading.
- HVAC system improvements – installing energy efficient systems with advanced controls.
- Energy efficient lighting – replacing incandescent lighting by compact fluorescent lighting (CFL) or LED lighting.
- Replacing inefficient equipment – replacing cathode ray tube (CRT) computer monitors with liquid crystal displays (LCD).
- Electromechanical improvements – installing power factor correcting capacitors to improve the power factor.

The main problem is that most investors are reluctant to invest in energy saving projects such as retrofit projects. This is because such projects are often not able to compete with other investments within the institutions or companies due to unclear benefits. But this is not the case if an investment in energy-efficiency projects is made with the help of decision making tools that can identify large monetary savings. Furthermore, this makes energy efficiency projects competitive with other projects. A decision can be made using the following two approaches [5–9]:

- In the first approach, an energy expert carries out an energy analysis of the building and several alternative scenarios will be developed and evaluated.
- In the second approach decision-making tools such as multi-objective or multi-criteria combined with simulations are applied to assist the decision maker to reach a final decision among a given set of alternative actions.

The multi-criteria technique in the second approach has been used to assist the designers to select the most feasible actions during the initial stages of a renovation project, for energy efficiency improvement of a building [9]. The major setback of this technique is that it is based on predefined sets of actions and

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* Corresponding author. Tel.: +27 12 4204335; fax: +27 12 3625000.
E-mail addresses: s25449274@tuks.co.za (E.M. Malatji), zhang@up.ac.za (J. Zhang), xxia@postino.up.ac.za (X. Xia).

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scenarios that should be pre-evaluated. In such a case there is no guarantee that the solution reached is the optimal one [7]. Due to the complexity of decision-making problems especially ones with multiple objectives, the multi-objective optimisation technique is a suitable candidate to model these problems, because it can explore potentially an unlimited number of alternatives. This technique is used by many researchers mainly with the objective to reduce the cost of the materials and to maximise energy savings. The possibility to use the multi-objective optimisation model to solve the decision problems that consider as many options as possible is widely accepted. [8] Simultaneously minimises the following three objectives: the energy consumption of the building; the initial investment cost; and the annual carbon dioxide emission. [9] Studies a similar problem to balance the energy, environment, financing and social factors. The hybrid decision system is suggested by [10] for sustainable renovation of office buildings and improvements in energy performance, where the decision-maker is facing the challenge of making trade-offs between renovation costs, environmental impacts and improved building quality. The weakness of these studies is that they do not consider the payback period of the investment as one of the objectives. They consider a case of unlimited funding which is not always possible because most of the time there are budget constraints. Another shortfall of these researches is that they do not perform the sensitivity analysis or the robustness test on the model. According to [11] every model has a high probability of having uncertainty with regard to some of its parameters. This issue can be addressed by performing the sensitivity analysis or the robustness test. In the study [12] a sensitivity analysis is used before the decision making to validate the robustness of the design decision related to the energy consumption and comfort. The study in [13] makes use of sensitivity analysis to predict the night cooling performance of internal convective heat transfer modelling and the result reveals that some choices of the convectional algorithm may affect the energy and predictions related to the thermal comfort. The study in [14] inspects the robustness of the methodology used to estimate the hourly energy consumption of a given building that considers discrepancies of the parameters within a building. The results show that the methodology can eliminate the errors caused by discrepancies. The research in this paper addresses these shortcomings of the previous researches by constructing a model that will maximise the energy savings and minimise the payback period of the investment, and there will be trade-off between the two if necessary. The contribution of this paper is the addition of the payback period of the investment as an objective, something that has never been considered by previous studies. A sensitivity analysis is performed to illustrate the robustness of the model. The model is constrained by budget, targeted energy savings and acceptable payback periods. This model also considers the time value of money by making use of the net present value (NPV). The research conducted by [8,9] present a model that is applicable to the design phase of the building, while the research under this study will present a model that can be used during the operation stage of the building. The model in this paper is applicable to many similar energy retrofit and renovation projects.

Because of the complexity of the multi-objective optimisation models, an easy way to solve them is to use the genetic algorithms (GA). GA can be viewed as a family of computational models that are inspired by evolution. To illustrate the effectiveness of the model obtained in this paper, GA is used to solve the multi-objective optimisation model. Note that other types of popular algorithms, such as particle swarm optimisation, simulated annealing, ant colony, and so forth, may also be applied to solve the obtained model.

The paper is organised as follows: in Section 2, an optimisation model for investment decision making in buildings energy-efficiency projects is formulated. In Section 3 the optimisation model is applied to a case study. The results and simulations of the case study are presented in Section 4. The conclusion is given in the last section.

2. The multi-objective optimisation model

2.1. Problem formulation

The modelling of the energy retrofit problem as a multi-objective optimisation problem is considered in this section. The optimisation model will help the decision-maker to select the most optimal actions to take in order to optimise the objectives. An initial investment will be given and a decision should be made to optimise the following objectives:

- Maximising energy savings and
- Minimising the payback period of the investment. The optimisation model is subjected to NPV, payback period, budget and the energy target constraints.

2.2. Optimisation model and constraints

Let x_i be a variable representing the quantity of type i facilities to be replaced during the energy retrofits, $1 \leq i \leq n$. x_i must be an integer because the number of facilities cannot be decimals. The optimisation variables of the optimisation model are (x, T) with $x = (x_1, \ldots, x_n)$ and T is the time frame of NPV that will be determined through inequality (4). Since the number of facilities that can be retrofitted is always limited, all the variables must be bounded by the inequality that follows:

$$0 \leq x_i \leq l_i, \quad i = 1, \ldots, n, \tag{1}$$

where l_i is the maximum number of type facilities allowable. The initial investment of the facilities is given by $I_0 = \sum_{i=1}^{n} x_i b_i$ and $B = \sum_{t=1}^{T} B_t$ is the total annual cost savings of the proposed alternative where $B_t = \sum_{i=1}^{n} a_i x_i c_i (1 + r^t))$ is the cost savings at time instant t. a_i is the total average annual energy savings of each facility is given by $a_i = \mathrm{EC}_{\mathrm{existing}} - \mathrm{EC}_{\mathrm{proposed}}$.

The two objectives are to minimise the payback period ($f_1(x)$) and to maximise the annual energy savings ($f_2(x)$),

$$f_1(x) = \frac{I_0}{B} = \frac{\sum_{i=1}^{n} x_i b_i}{\sum_{t=1}^{T} \sum_{i=1}^{n} a_i x_i c_i (1 + r^t)}, \tag{2}$$

$$f_2(x) = a_1 x_1 + a_2 x_2 + \ldots + a_n x_n, \tag{3}$$

subject to:

$$\mathrm{NPV} := \sum_{t=0}^{T} \frac{(B_t - C_t)}{(1 + d_t)^t} - I_0 \geq 0, \tag{4}$$

$$0 \leq T \leq \xi, \tag{5}$$

$$b_1 x_1 + b_2 x_2 + \ldots + b_n x_n \leq \beta, \tag{6}$$

$$f_1(x) \leq 0.1Z, \tag{7}$$

$$f_2(x) \geq 0.1\alpha, \tag{8}$$

where a_i is the average annual energy savings of ith type facility in kWh, b_i is the unit price of the ith type facility, c_i^t is the cost of electricity in \$/kWh at time t, B_t represents the benefits in year t due to energy savings (\$), C_t represents the operational cost in year t (\$), d_t is the discount rate at time t, ξ the integer that makes NPV non negative, β is the budget of the project (\$), α is the energy baseline (kWh), r^t is the rate at which electricity price increases, $\mathrm{EC}_{\mathrm{existing}}$ is the energy consumption of the of the existing facilities, and $\mathrm{EC}_{\mathrm{proposed}}$ is the energy consumption of the of the proposed facilities.