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Optimal selection of energy efficiency measures for energy sustainability of existing buildings

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ABSTRACT

This study is motivated by the need to increase energy efficiency in existing buildings. Around 33% of the energy used in the world is consumed in the buildings. Identifying and investing in the right energy saving technologies within a given budget helps the adoption of energy efficiency measures in existing buildings. We use a mathematical programming approach to select the right energy efficiency measures among all the available ones to optimize financial or environmental benefits subject to budgetary and other logical constraints in single- and multi-period settings. We also present a business model to offer energy efficiency measures as a service. By using a real case study of a university campus, all the relevant energy efficiency measures are identified and their effects are determined by using engineering measurements and modelling. Through numerical experiments using the case data, we investigate and quantify the effects of using environmental or financial savings as the main objective, the magnitude of benefit of using a multi-period planning approach instead of a single-period approach, and also feasibility of offering energy saving technologies as a service. We show that substantial environmental and financial savings can be obtained by using the proposed method to select and invest in technologies in a multi-period setting. We also show that offering energy efficient technologies as a service can be a win–win–win arrangement for a service provider, its client, and also for the environment.

1. Introduction

Emissions from burning fossil fuels are the primary cause of the rapid growth in atmospheric carbon dioxide (CO_2) [6]. Natural gas and oil that are primarily used for heating and cooling as well as electricity generation in buildings play an important role in CO_2 emissions [25]. Energy usage in buildings is responsible for approximately 33% of the total of final energy consumption and an important source of energy-related CO_2 emissions worldwide [26]. In OECD countries, buildings cause about 30% of national CO_2 emissions from the consumption of fossil fuels [19].

One of the ways of improving energy sustainability is increasing energy efficiency in existing buildings. However, investment costs for installing and/or replacing technologies with more efficient ones can be seen by the building owners as an obstacle to achieve improvements in energy consumption.

Replacing an existing technology in a building with a more energy efficient one decreases energy consumption. Consequently, this change affects both future CO_2 emissions and also future energy expenditures. Therefore, the initial investment decision for the new technologies should be given by taking future energy expenditure savings and also reductions in CO_2 emissions into account. This study is motivated by the need to use an analytical approach to select the right energy efficiency measures for improving energy efficiency in existing buildings with both environmental and financial considerations.

1.1. Literature review

Selecting and implementing energy efficiency measures have received increasing attention in recent years. Aaki et al. [1] discuss the decision making process to select and implement energy efficiency measures in manufacturing companies. Muthulingam et al. [18] discuss the adoption of energy efficiency improvement recommendations by small and medium-sized manufacturing companies.

Increasing energy efficiency of buildings involves implementing various energy efficiency measures (also referred as energy saving technologies in this study) ranging from the ones with the lowest cost such as setting the domestic hot water system optimally, to replacing electrical fixtures, installing an exterior thermal sheathing to buildings, replacing doors or window joists,

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adding insulation in attics or wall cavities, and to changing heating systems with more efficient ones [11]. Parker et al. [20] report an approximately 25–30% increase in energy saving for houses built before the 1940s and 12% for houses built in the 1990s can be reached by taking advantage of these technologies. Bell and Lowe [5] report that retrofitting of four houses in the UK reduced the energy requirements by 35% with improved insulation, and it is possible to achieve 50% improvement by implementing additional measures.

Similar energy efficiency measures and their benefits are also reported in other studies, e.g. Ardente et al. [3], Mahlia et al. [17], Sadineni et al. [23], Hens and Verbeeck [10], and Houri and Khoury [12]. However, these studies do not present a general method that is applicable to a wide range of buildings and energy efficiency measures to select the technologies among all the available ones according to their energy consumption, energy cost, and CO_2 emission to optimize a given objective function subject to budgetary constraints. Alanne [2] presents a multi-criteria knapsack model to select renovation actions in buildings. Kolokotsa et al. [13] analyze decision support methodologies to select energy efficiency measures in buildings. Kolokotsa et al. [22] present an integrated approach that combines simulation and optimization decision to select retrofit decisions in a single period setting.

Implementing energy efficiency measures requires finding a feasible way to finance these projects [21]. In this study, we also investigate the feasibility of offering energy saving technologies as a service. In this arrangement, a firm offers making all the necessary energy saving technology investments for a client in exchange of getting a fraction of the savings in energy expenditures for a predetermined time period. This business model is used by Energy Service Companies (ESCOs). For reviews of ESCOs, the reader is referred to Goldman et al. [9] and Vine [27]. For the success of this business model, the right set of technologies must be selected given the budgetary constraints and the objectives regarding CO_2 emissions and financial returns. The mathematical programming approach presented in this study can be used to select the right technologies.

The existing literature on energy efficiency measures can be grouped into two: the ones that focus on engineering aspects of identifying, selecting, and implementing energy efficiency measures, and the ones that focus on managerial and economical issues of deciding and implementing these measures. The first group of studies use specific cases without much consideration of economical issues. On the other hand, the latter ones focus on the principles of selecting efficiency measures, and use these principles to provide *insights* without discussing its implementation in large projects in detail.

1.2. Overview

In this study, we use a mathematical programming approach to select the right energy efficiency measures among all the available ones to optimize financial or environmental benefits subject to budgetary and other logical constraints in single- and multi-period settings.

We use Boğaziçi University Kilyos Campus as a case study to investigate and quantify the effects of using environmental or financial savings as the main objective, the advantages of using a multi-period planning approach to a single-period approach, and also feasibility of offering energy saving technologies as a service. For this case, the primary objective was set as maximizing the environmental benefits within a given budget as a part of their sustainable and green campus initiative.

Three objectives, maximizing reductions in CO_2 emissions, maximizing cost savings, and maximizing energy savings are interrelated: the source of emissions savings is reduction in energy consumption. If the cost savings are maximized, it is expected that reductions in CO_2 emissions and energy efficiency will also be improved. One may argue that the difference between maximizing cost savings and CO_2 emission savings will not be significant for the amount of CO_2 emission that will be saved, and the additional cost savings can be used for other sustainability and green campus initiatives. The method presented in this study allows us to *quantify* the effects of using different objective functions.

For the case of Boğaziçi University Kilyos Campus, all the relevant energy efficiency measures for all the buildings in the campus are identified and their expected effects on energy savings, CO_2 emissions, and costs are determined by using detailed technical, engineering measurements and modelling. Therefore this study combines architectural, engineering, and operations research approaches to present the effectiveness of the optimization approach to select energy saving technologies to improve energy efficiency in existing buildings.

We use an optimal selection method that is based on a mathematical programming formulation to select and invest the right energy saving technologies to maximize the financial, energy, or CO_2 savings in a single- and multi-period setting involving a high number of alternative investment alternatives.

By using the large-scale case study where the parameters are determined based on careful engineering measurements, we *quantify* the benefits of the proposed multi-period selection method compared to single-period selection of investments under a budgetary constraint. We note that although it can be stated that a multi-period formulation will be beneficial over a single-period formulation, without using a particular case study, determining *how much* additional benefit can be obtained is of interest to practitioners.

In a similar way, we also *quantify* the effects of using financial, environmental, or energy savings as the objective of the optimization problem to select the energy saving methodologies on the energy usage, financial and environmental gains that will be achieved. Finally, we analyze the feasibility of a business model that offers investments in energy saving technologies as a service and show that this business model offers benefits to the service providers, its customers, and also to the environment.

The main contributions of this study are linking economic and engineering aspects of the process of selecting and implementing energy efficiency projects, and by using the data on a large-scale project, reporting the *magnitude* of benefits of various evaluation criteria in selecting and implementing energy efficiency measures in a multi-period setting by offering investments in these technologies as a service.

Based on this analysis, we show that substantial environmental and financial savings can be obtained by using the proposed method to select and invest in technologies in a multi-period setting. We also show that offering energy efficient technologies as a service can be a *win–win–win* arrangement for a service provider, its client, and also for the environment. The firm that offers the service can gain substantial financial returns. The customer pays a fraction of its energy bill with this agreement. Furthermore realized energy savings will decrease CO_2 emissions, and also ease the burden on future energy investments.

The organization of the remaining part of this paper is as follows. In Section 2, the mathematical programming problem for selection of energy saving technologies is presented for both single-period and multi-period settings. In Section 3, the case of improving energy efficiency of Boğaziçi University Kilyos Campus is discussed. Numerical results that are based on the data collected and measured for this case are given in Section 4. Finally, the conclusions are given in Section 5.

2. Mathematical programming problem for selection of energy saving technologies

The technology selection problem we consider is selecting the technologies to invest among all the available technologies that