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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 are available to optimize an objective function subject to given constraints.

For energy saving technologies, there exists an investment cost for each technology. Investing in a particular technology yields a specific amount of energy saving, therefore yields a corresponding amount of cost saving, and also CO_2 saving. The primary constraint in selecting the technologies is the limitation of the budget that will be used to invest in energy-saving technologies. There might be additional logical constraints that limit the selection of technologies depending on the selection of other technologies.

We consider both single-period and multi-period problems. In the single-period problem, the decision maker selects the technologies and invests all of these technologies at once for the current period. Accordingly, the future cost, energy, and CO_2 savings are achieved from the initial investment.

In the multi-period problem, the decision maker considers a planning problem over T periods. With the objective of maximizing the total savings over all period, the decision maker decides on which technologies to invest at each time period. Since each investment yields future financial gains as a result of energy cost savings, these financial gains can be used to invest in other technologies in later periods. As a result, it is possible to start with a low initial budget and achieve substantial gains by using the accumulated savings as a revolving fund for future investments. In Section 4, we analyze this snowball effect by comparing the savings achieved by using multi-period planning to the savings obtained by using singe-period planning.

2.1. Technology selection problem in single period

We consider the problem of selecting technologies among N available technologies. The basic question we will answer is the following: *if you have B dollars to invest in energy saving technologies, in which technologies should you invest in order to maximize reductions in CO_2 emissions, maximize energy savings, or maximize cost savings?*

The selection of technologies to maximize the savings is a binary knapsack problem. The decision variables are binary indicating whether a particular technology is invested or not. The objective function is maximizing the energy expenditure savings, maximizing energy savings, or maximizing reductions in CO_2 emissions. The constraints are related to the budgetary limitation for the initial investment and other logical constraints related to the selection of different technologies.

Using binary knapsack problem to select projects to optimize a given objective function subject to a set of constraints is a well-studied problem in operations research, e.g., Beaujon et al. [4], Schmidt [24], Kyparisis et al. [14]. The same approach is also used to select renovation actions in construction [2]. In this paper, we use the established methodologies to solve these problems and focus on formulation, data acquisition, objective setting, and quantification of the benefits.

It is possible to formulate a multi-objective optimization problem to consider environmental and financial benefits simultaneously. However, as discussed in the preceding section, the main motivation of this study is analyzing the effects of using environmental *or* financial benefits as the main objective function for selecting the technologies to invest with a given budget.

Let c_i be the cost of technology i (USD \$), e_i be the amount of CO_2 (kg) that will be saved by using technology i, d_i be the energy saving (kWh) that will result from technology i, and s_i be the financial saving (USD \$) resulting from the energy savings due to technology i, $i = 1, \ldots, N$.

In this paper, we assume that a given technology does not need replacement in the planning period. Considering the energy efficiency measures available for existing buildings, this assumption is a reasonable one since the useful life of these projects is quite long.

All the savings are given for the single period under consideration. The total budget available for investments is denoted with B. The decision variable of investing in technology i is x_i that is 1 if technology i is invested and 0 otherwise.

When the objective is maximizing the reductions in CO_2 emissions, the mathematical program is given as

$$\text{maximize} \quad \sum_{i=1}^{N} e_i x_i \tag{1}$$

$$\text{subject to} \quad \sum_{i=1}^{N} c_i x_i \le B, \tag{2}$$

$$\sum_{i \in \Omega_j} x_i \le 1, \quad j = 1, \ldots, J \tag{3}$$

$$x_i \in \{0, 1\}, \quad i = 1 \ldots N. \tag{4}$$

where Ω_j is the set of mutually exclusive alternative projects that require at most only one of them can be selected in this set and J is the number of sets. If there are other logical constraints that limit the selection of the decision variables, these constraints need to be added to this base model.

In order to select the technologies to maximize the financial savings, the objective function of the above mathematical program is changed to

$$\text{maximize} \quad \sum_{i=1}^{N} s_i x_i. \tag{5}$$

Similarly, in order to select the technologies to maximize the energy savings, the objective function given in Eq. (1) is replaced with

$$\text{maximize} \quad \sum_{i=1}^{N} d_i x_i. \tag{6}$$

Note that these three objective functions are interrelated: the source of emissions savings is reduction in energy consumption. In other words, e_i is a function of d_i; the emission savings can be evaluated by using a monetary equivalent, for example by using spot price in a carbon market. Since the relative importance of these measures is different for non-profit and for profit companies, using different objective functions yields different set of energy efficiency measures. For example, for the case of Boğaziçi University Kilyos Campus, the primary objective is maximizing the environmental benefits with the allocated budget for the project. On the other hand, analyzing a business model that is based on offering energy saving technologies as a service requires considering both environmental and financial objectives. In Section 4, we consider the trade-off between using maximizing the cost, energy, or CO_2 savings as the objective function by using the case study.

2.2. Technology selection problem in multiple time periods

In the multi-period setting, the decision variables include both selection of the technology and also timing of the investment in each selected technology. After the initial investment, future savings in energy expenditures are used to accumulate cash to invest in other technologies. Therefore, substantial savings can be achieved by using a relatively low level of initial investment. In this case, there will be additional constraints related to the cash flow dynamics in subsequent periods. Similar models were developed to optimize independent projects over multiple time periods, e.g., Dickinson et al. [8] and Liberatore [15].

The planning horizon includes T periods. We define $c_{i,t}$ as the investment required for project i at the beginning of period t, $e_{i,t}$ as the CO_2 saving achieved at the end of period t by using project i, $s_{i,t}$ as the cost saving achieved at the end of period t by using project i, b_t as the money available for investment at the beginning of period t, r as the interest rate for the period, and B as the initial budget available for investments. The length of the period is set as 1 year. The beginning time of a given period can be set to any date without loss of generality. If it is required, effects of making investments at different times in each period can be captured precisely by setting the length of the period to a shorter duration, for example, as 1 month.

Changes in prices, efficiency, or technology are captured in time varying parameters of $e_{i,t}$ and $s_{i,t}$ in a deterministic way. The cost saving achieved is calculated by using the energy saving and also possible energy price increase in the contract period.

The decision variable is $x_{i,t},\ i=1\ldots N, t=1\ldots T$ which is 1 if project i is invested at the beginning of year t and 0 otherwise. We also define a logical variable $z_{i,t}$ which becomes 1 when technology i is invested at the beginning of time t' and stays 1 until time T. When $z_{i,t}$ is 1, energy and financial savings are received in period t.

Then the mathematical programming formulation for selection of energy-saving technologies to maximize the total CO_2 savings in T periods is given as

$$\text{maximize} \quad \sum_{i=1}^{N}\sum_{t=1}^{T} e_{i,t} z_{i,t} \tag{7}$$

$$\text{subject to} \quad b_t = \left(b_{t-1} - \sum_{i=1}^{N} c_{i,t-1} x_{i,t-1}\right)(1+r) + \sum_{i=1}^{N} s_{i,t-1} z_{i,t-1}, \quad t=2,\ldots,T, \tag{8}$$

$$\sum_{i=1}^{N} c_{i,t} x_{i,t} \le b_t, \quad t=1,\ldots,T, \tag{9}$$

$$z_{i,t} = \sum_{t'=1}^{t} x_{i,t'}, \quad t=1,\ldots T, i=1,\ldots,N, \tag{10}$$

$$\sum_{t=1}^{T} x_{i,t} \le 1, \quad i=1,\ldots,N, \tag{11}$$

$$\sum_{i \in \Omega_j} x_{i,t} \le 1, \quad t=1,\ldots,T, j=1,\ldots,J, \tag{12}$$

$$b_t \ge 0, \quad t=1,\ldots,T, \tag{13}$$

$$b_1 = B, \tag{14}$$

$$x_{i,t} \in \{0,1\}. \tag{15}$$

In the above formulation, the cash flow dynamics is captured in Eq. (8). For example, in period $t-1$, one can use all or a portion of the available money at a given time period b_{t-1} to invest in different projects. Once the investments are completed in a given period, it is possible to have a portion of the initial money available for investment not used. If this is the case, we assume that the unused money $(b_{t-1} - \sum_{i=1}^{N} c_{i,t} x_{i,t-1})$, collects an interest with an interest rate of r from the financial market until the next period. Therefore, at the beginning of the following period, the unused money from the previous period that has increased with the interest rate will be available for investments in other technologies. Furthermore, all the investments in energy-saving technologies yield energy savings that correspond to energy cost savings for the future periods. We assume that these cost savings, $\sum_{i=1}^{N} s_{i,t-1} z_{i,t-1}$ will be available for investment together with the available money from the previous period $(b_{t-1} - \sum_{i=1}^{N} c_{i,t-1} x_{i,t-1})(1+r)$. This will determine the available money for investment at the next period t, b_t.

Eq. (9) is the budget constraint for time t. Eq. (10) defines the logical variable $z_{i,t}$. Eq. (11) shows that the decision to invest in one project is given only in one particular time period. That is, you cannot invest in the same project multiple times during the planning horizon. Eq. (12) indicates that at most one project from each set Ω_j can be chosen. Eq. (13) guarantees that the investment in period t is limited by the money available in that period; and Eq. (14) defines the initial budget.

The objective function of the maximization problem can also be set as maximizing the net present value (NPV). Note that when an initial budget of B is provided, at each time period, the available money at that period including the savings from previous technologies that were invested in earlier periods are used to finance the investments in new technologies in that period. The remaining money is then carried to the next period with an interest collected from a financial institution. Since all the surpluses are invested at the end of each period, the net cash flow in each time period is zero. However, at the end of the last period, the surplus will not be invested further. Accordingly, the net present value of investing in multiple projects in multiple time periods is expressed as

$$\text{NPV} = \left(\left(b_T - \sum_{i=1}^{N} c_{i,T} x_{i,T}\right)(1+r) + \sum_{i=1}^{N} s_{i,T} z_{i,T}\right)(1+r)^{-T} - B. \tag{16}$$

In the case of maximizing NPV instead of maximizing the reductions in CO_2 savings, the objective function in Eq. (7) is replaced with

$$\text{maximize} \quad \text{NPV}. \tag{17}$$

Note that if the objective is maximizing financial benefits at the end of the planning period, it is possible to accumulate cash without investing in any technology especially when the financial return of investing in these technologies is lower than the market interest rate. Alternatively, starting with a low initial budget, this method can be used to accumulate revolving funds to invest in other energy-saving technologies that cannot be invested with the initial funds.

In this paper, we do not consider possible interaction between the various technologies. Implementing a particular technology at an earlier time on a given building may affect the potential energy savings that will be realized by implementing another technology on the same building at a later time. For example, energy savings obtained from replacing the boiler will be lower if the building is installed with insulation at an earlier time compared to the case where the building has no insulation at the time of boiler replacement. In large projects, such as the one we analyzed in Section 3, most of the energy efficiency measures, such as projects in different buildings of the campus, do not interact with each other. If they interact, these effects can be captured partially in time-dependent saving parameters $e_{i,t}$ and $s_{i,t}$. Capturing the full effect of these interactions requires a different formulation that considers the sequence of implementing these projects. However, the main difficulty will not be in the mathematical formulation but in determining the parameters that will be used by this formulation. This requires developing an energy consumption model of each building with all combinations of available energy efficiency measures.

The multi-period model presented in this section takes the approach that the future financial savings resulting from improving energy efficiency are directed as a fund to investing only in other energy efficiency measures or in the short-term financial market. This is the case when an organization has a long term contract with an energy provider; and it does not consider other

Table 1
Optimization problems for selecting energy saving technologies.

Objective	Singe time period	Multiple time period		
	Base model	Base model	Minimum NPV	Profit sharing
CO_2	Model M11 (1), (2)–(4)	Model M12 (7)–(15)	Model M13 (7)–(15) and (21)	Model M14 (7), (18), (9)–(15)
NPV	Model M21 (5), (2)–(4)	Model M22 (17), (8), (9)–(15)		Model M24 (19), (18), (9)–(15)
Energy	Model M31 (6), (2)–(4)			

investment options in financial markets at the end of each time period. In the next section, we present a business plan to offer energy saving technologies as a service that is based on using the multi-period model for selecting the energy-saving technologies. The multi-period model will be used by the service provider to set the terms of the contracts of its service.

2.3. Analysis of a business model to offer energy saving technologies as a service

In the previous section, we presented a method to select the best energy saving technologies among all the available technologies in order to maximize CO_2 or cost savings. In this section, we analyze a business model to select and invest in energy saving technologies as a service offered to customers [28]. We 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, denoted with Δ, for a predetermined time period T. The contract is then determined with two parameters (Δ, T). The total energy cost saving from investing in energy saving technologies in each period is shared between the client that receives Δ fraction of the total saving and the service provider that receives the remaining $1-\Delta$ fraction.

For example, if the service provider and its client agree on a contract (80%,5), 80% of the energy cost saving will be kept by the client while the service providers gets the remaining 20% for a period of 5 years. With the agreement, the service provider makes the necessary investments in energy-saving technologies in such a way that the 20% of the energy cost savings will be sufficient to cover the cost of the initial investment and also yield an acceptable return on the investment. This agreement will also be beneficial for the customer since it will decrease its energy cost and keep 80% of the savings without making any investment. As a result of implementing energy-saving technologies, energy consumption and CO_2 emissions will also be reduced. Therefore, the service provider, the client, and the environment will benefit from this arrangement.

This business model allows a service provider to specialize in energy efficiency projects. By implementing such projects in different settings, a service provider provides value to its customers not only by removing the burden of making an initial investment in energy efficiency measures, but also by providing expertise in identifying, selecting, and implementing these projects. Furthermore, a firm that specializes in offering energy saving technologies as a service will generate a larger purchasing volume for energy saving technologies compared to its customers that may purchase these technologies only once. This way, the service provider creates an additional advantage compared to an organization that implements these projects itself.

The multi-time period model presented in the preceding section can be used for the service provider to set the parameters of the contract that are given as Δ and T. Furthermore the financial viability of the initial investment can be assured by extending the basic model. In this section we present two extensions of the basic multi-period planning problem to analyze the business plan to offer energy saving technologies as a service.

2.3.1. Model with sharing cost savings between service provider and customer

When the company guarantees a predetermined energy cost saving rate Δ to its customer, the company collects $(1-\Delta)s_{i,t}$ of the energy saving obtained in period t from technology i while the customer receives $\Delta s_{i,t}$. For this case, the financial flow constraint of the base model given in Eq. (8) is modified to reflect that only $1-\Delta s_{i,t}$ portion of the energy cost saving after giving its part to the customer based on the contract will be available for investments in energy saving technologies:

$$b_t = \left(b_{t-1} - \sum_{i=1}^{N} c_{i,t-1}x_{i,t-1}\right)(1+r) + \sum_{i=1}^{N}(1-\Delta)s_{i,t-1}z_{i,t-1},$$
$$t = 1, \ldots, T. \tag{18}$$

The objective function for the CO_2 saving problem is the same as the one given in Eq. (7). For the NPV maximization problem, the objective function is given as

$$\text{maximize} \quad \text{NPV}' \tag{19}$$

where the net present value for the case where the cost savings are shared between the company and its client is derived similar to Eq. (16), and given as

$$\text{NPV}' = \left(\left(b_T - \sum_{i=1}^{N} c_{i,T}x_{i,T}\right)(1+r) + \sum_{i=1}^{N}(1-\Delta)s_{i,T}z_{i,T}\right)(1+r)^{-T} - B. \tag{20}$$

2.3.2. Model with the minimum desired profit

One way of managing the trade-off between setting the objective as maximizing the financial benefits versus environmental benefits is adding a constraint for the minimum desired financial benefit while maximizing the environmental benefit.

In order to assure the sustainability of the business model, investment in energy saving technologies should be financially attractive for the service provider. The basic mathematical program presented in the preceding section can be extended to add a constraint that guarantees a certain value of NPV that is measured as a multiple of the initial investment B. This multiple is referred as the profit rate and denoted with ρ.

The mathematical constraint of NPV is

$$\text{NPV} \geq \rho B. \tag{21}$$

By adding this constraint to the base model, the service provider can use the mathematical programming formulation to select and invest in energy saving technologies to maximize the reduction in CO_2 emissions while ensuring that the initial investment brings the desired level of return depending on the duration of the contract.

2.4. Optimization problems for selecting energy saving technologies

In Section 4, the models presented in this section are analyzed by using the case study that will be discussed in Section 3. We presented both single- and multi-period models; each optimization model can be analyzed with an objective to maximize environmental benefits or financial benefits; and we also presented extensions of the multi-period base model to analyze the business model. This results in using eight different optimization models in our analysis. Table 1 summarizes these models and gives the corresponding objective function and the constraints.

3. A case study: Boğaziçi University Kilyos campus

Kilyos Campus that is a remote campus of Boğaziçi University, located in the northern part of Istanbul on the Black Sea cost that is subject to northern winds. The campus consists of seven buildings with a total flat area of 25,040 m^2 and 700 students. The average natural gas and electricity consumption and the current CO_2 emissions for this campus are given in Table 2.

University campuses are small scale self-contained living environments where the residents spend their complete daily life cycle within the buildings at the site. So analyzing a university campus to study energy efficiency measures gives insights that can be applicable to larger living environments. Selecting a campus complex instead of a single stand-alone building for the study makes it possible to include existing buildings of different sizes, layouts, functions, and levels of energy efficiency. Furthermore, the effect of buildings on each other and the impact of common areas and common mechanical systems on the energy efficiency of the whole complex are captured in the analysis.

In his PhD thesis, Çamlıbel [7] identified a set of energy efficiency measures for this campus. Based on evaluation of architectural structure, technical specification, and expert interviews, 42 different energy efficiency measures are identified to improve the energy efficiency of the buildings for this campus. These energy Efficiency Measures (EEM) are given in Table 3 with their codes and indices.

These energy efficiency measures include improvement of the natural gas heating system that is the main source of energy consumption in the campus, retrofit of exterior wall and roof insulation, improvement of the lightning system, as well as creating sunrooms on roof and balconies to improve energy efficiency in a passive way by using architectural design.

By using a detailed technical and mechanical modelling and measurement, the expected energy savings from each energy saving technology and the corresponding reduction in CO_2 emissions and energy costs are also identified for each energy saving technology. IZODER TS 825 software that is based on European Standard (6946:2007) was used for calculating the shell *U*-values

Table 2
Annual average energy consumption and CO_2 emission levels at Boğaziçi Kilyos campus.

Consumption and Emission	Electricity	Natural gas	Total
Total consumption (kWh)	959,480	2,276,839	3,256,319
Total CO_2 emission (kg)	604,339	532,780	1,137,119

Table 4
Technologies investment cost and saving amounts wrt kWh,$ and CO_2 for Kilyos campus.

No.	Code	Energy type	Investment $	kWh Saving/ year	$ Saving/ year	kg CO_2 saving/ year
1	D1	Heating	1.250	76.827	3.129	17.977
2	H1	Heating	500	3.295	134	771
3	I1	Heating	1.250	55.557	2.263	13.000
4	A2	Heating	1.071	23.443	955	5.486
5	B2	Heating	1.071	23.443	955	5.486
6	C2	Heating	964	21.099	859	4.937
7	E2	Heating	2.330	50.989	2.077	11.931
8	F2	Heating	6.750	229.189	9.335	53.630
9	I2	Heating	1.969	43.077	1.754	10.080
10	D3	Heating	41.250	250.005	10.182	58.501
11	A4	Heating	5.850	61.050	2.486	14.286
12	B4	Heating	5.850	60.764	2.475	14.219
13	C4	Heating	1.300	17.402	709	4.072
14	I4	Heating	9.100	63.969	2.605	14.969
15	D5	Electricity	10.938	24.599	3.296	15.178
16	G5	Electricity	12.500	37.426	5.015	23.092
17	H5	Electricity	1.563	1.972	264	1.216
18	I5	Electricity	6.250	17.200	2.305	10.613
19	A6	Heating	34.402	95.692	3.514	22.392
20	B6	Heating	34.402	95.611	3.511	22.373
21	C6	Heating	17.084	27.329	1.004	6.395
22	E6	Heating	33.448	156.501	5.747	36.621
23	F6	Heating	22.182	69.278	2.544	16.211
24	I6	Heating	38.998	92.882	3.411	21.734
25	A7	Heating	30.850	81.789	3.003	19.139
26	B7	Heating	30.850	81.210	2.982	19.003
27	C7	Heating	15.320	23.286	855	5.449
28	E7	Heating	29.995	152.049	5.583	35.579
29	F7	Heating	19.892	59.272	2.177	13.870
30	I7	Heating	34.972	79.314	2.912	18.559
31	A8	Heating	27.055	61.993	2.276	14.506
32	B8	Heating	27.055	61.948	2.275	14.496
33	C8	Heating	13.436	17.706	650	4.143
34	E8	Heating	26.305	145.914	5.358	34.144
35	F8	Heating	17.445	45.575	1.674	10.664
36	I8	Heating	30.670	60.237	2.212	14.095
37	D9	Electricity	3.750	4.455	597	2.749
38	G9	Electricity	6.250	11.880	1.592	7.330
39	I9	Electricity	3.750	5.940	796	3.665
40	A10	Heating	65.655	31.912	1.172	7.467
41	B10	Heating	65.655	31.890	1.171	7.462
42	E10	Heating	119.824	65.837	2.418	15.406

Table 3
Energy efficiency measures at Boğaziçi Kilyos campus.

EEMS	Dorm I N-Block	Dorm I S-Block	Dorm I Fac. Apts.	Prep Sch Bldg A	Prep Sch Bldg B	Hotel	Dorm II
Optimization of domestic hot water system	D1 (1)	D1 (1)	D1 (1)	–	–	H1 (2)	I1 (3)
Heating system piping insulation	A2 (4)	B2 (5)	C2 (6)	E2 (7)	F2 (8)	–	I2 (9)
Renovation of boiler	D3 (10)	D3 (10)	D3 (10)	–	–	–	–
Installation of thermostatic valves	A4 (11)	B4 (12)	C4 (13)	–	–	–	I4 (14)
Change of light bulbs' ballasts	D5 (15)	D5 (15)	D5 (15)	G5 (16)	G5 (16)	H5 (17)	I5 (18)
Envelope insulation environments – 6 cm	A6 (19)	B6 (20)	C6 (21)	E6 (22)	F6 (23)	–	I6 (24)
Envelope insulation environments – 5 cm	A7 (25)	B7 (26)	C7 (27)	E7 (28)	F7 (29)	–	I7 (30)
Envelope insulation environments – 4 cm	A8 (31)	B8 (32)	C8 (33)	E8 (34)	F8 (35)	–	I8 (36)
Installation of variable speed drive pumps	D9 (37)	D9 (37)	D9 (37)	G9 (38)	G9 (38)	–	I9 (39)
Trombewall application	A10 (40)	B10 (41)	–	–	–	–	–
Creating sunrooms on roof and balconies	–	–	–	E10 (42)	–	–	–

of the buildings and their heating energy demand. This demonstrates whether or not the buildings comply with the local insulation codes. LEED and Energy Star software were used to assess the energy consumption and CO_2 emission levels with the implementation of a given energy efficiency measure.

Table 4 shows the investment cost, saving amounts of energy (kWh), money (USD) and CO_2 (kg) for each energy efficiency measure that is identified for the Kilyos Campus. Table 4 indicates the type of energy saving (heating or electric energy) achieved by using each technology. Since natural gas is used for heating, a conversion factor of 0.234 kg/kWh is used to determine the amount of CO_2 emission due to natural gas consumption, and a conversion factor of 0.617 kg/kWh is used for CO_2 emission due to electric energy consumption reported in Column 7. Similarly, the financial savings reported in Column 6 are based on whether the proposed energy efficiency measure improves heating energy obtained from natural gas or electric energy consumption. Natural gas and electricity prices (USD/kWh) for the campus are then used to determine the financial savings reported in Column 6.

We note that composing the data given in Table 4 required close to 2 years of substantial effort in terms of technical measurements, and also required engineering and architectural expertise as reported in the PhD thesis of Çamlıbel [7].

In this study, we first give the analysis of this case in a single-period setting, and then extend the single-period model to multi-period model and also propose extensions of the multi-period model to analyze the feasibility of a business model to offer energy saving technologies as a service. In the next section, we use the data for Kilyos Campus to analyze the effectiveness of the multi-period technology selection model in order to quantify the savings that can be obtained by selecting and investing in the best technologies to achieve the optimal level of financial and environmental benefits, and investigate the feasibility of the business model to offer energy saving technologies as a service.

Among the Energy Efficiency Measures identified, the measures related to Envelope Insulation Retrofit with 4 cm, 5 cm, and 6 cm options for a given building are mutually exclusive. In other words, only one of these options can be selected for a given building. Accordingly, the mutually exclusive project sets (Ω_j given in Eq. (3)) are defined as $\Omega_1 = \{19, 25, 31\}$, $\Omega_2 = \{20, 26, 32\}$, $\Omega_3 = \{21, 27, 33\}$, $\Omega_4 = \{22, 28, 34\}$, $\Omega_5 = \{23, 29, 35\}$, and $\Omega_6 = \{24, 30, 36\}$. Then Eq. (3) can be set accordingly.

4. Numerical results

The data collected for the energy efficiency measures identified for Kilyos Campus given in Section 3 are valuable to analyze the effectiveness of the methodology presented in this study and also the feasibility of the proposed business model to offer energy saving technologies as a service. In this section, we focus on three questions:

- *What are the effects of using financial savings, energy savings, or CO_2 emission savings as the objective function of the optimization problem?*
- *What is the magnitude of benefit of using a multi-period technology selection method over a single-period selection of technologies?*
- *Is offering energy saving technologies as a service a beneficial approach for the service provider, its customers, and also for the environment?*

In order to investigate and quantify the answers to these questions, the mixed-integer linear programming formulations of the technology selection problem for the single-period and multi-period cases described in Section 2 and given in Table 1 are solved by using the data for the Kilyos Campus presented in Section 3. CPLEX 12.1 solver with MATLAB interface is used for the solution of the problems.

The single-period model has N binary variables and $J+1$ constraints. On the other hand, the base model for the multi-period problem has $2NT$ binary variables, $T-1$ continuous variables, and $(N+J+3)T+N$ constraints. Since there are 42 energy efficiency measures and 6 mutually exclusive technology sets for the case study, the single-period problem has 42 binary variables and 7 constraints and the base model for the multi-period problem has $84T$ binary variables, $T-1$ continuous variables, and $51T+6$ constraints. The longest planning horizon analyzed for the multi-period problem is 30 years. Analysis of this problem requires solving a problem with 2520 binary variables, 29 continuous variables, and 1536 constraints. These problems can easily be solved to optimality by using CPLEX running on a PC. The solution times are very fast. Therefore we do not report the computational times and focus on the results obtained by solving these problems.

4.1. Using financial, energy, or CO_2 savings as the objective function of the single period problem

The optimization approach presented in Section 2.1 allows a decision maker to select the energy saving technologies among all the available ones in the best way possible given the budgetary and other logical constraints according to a given objective. The objective of the optimization problem can be maximized by the reductions in CO_2 savings, maximized by the financial savings, or maximized by the energy savings. All three objectives are interrelated with each other. Investing in energy saving technologies yields reduction in energy usage; reduction in energy usage yields both financial savings and also reduces CO_2 savings. The formulations of these problems are given in Table 1: Model M11 for maximizing the reductions in CO_2 emissions, Model M21 for maximizing the financial savings, and Model M31 for maximizing the energy savings.

For the Kilyos Campus, Fig. 1 (a), (b), and (c) depict the optimal results obtained for given budget levels when the objective of the optimization problem is set to maximizing the CO_2 emission savings, financial savings, and energy savings respectively. Analyzing the selected technologies for given budget levels shows that the optimization problem usually proceeds with selecting the technologies that have higher desired savings per dollar of cost until the budget is used. This is similar to the greedy algorithms that are used to obtain a heuristic solution of the Knapsack problem [16].

Fig. 1(c) shows that it is possible to decrease the energy usage of Kilyos Campus by using a relatively low budget. For example, an investment of \$100,000 brings an energy saving of over 1 MWh in a year that corresponds to 30% saving for Kilyos Campus (Table 2). When the objective is maximizing the financial savings, Fig. 1 (b) shows that it is possible to select the energy saving technologies in such a way that the same amount of investment brings an annual saving of close to \$50,000, and therefore gives a pay-back period of close to 2 years. Similarly, when the objective is maximizing the CO_2 savings, Fig. 1(a) shows that an investment of \$100,000 yields a reduction of around 250,000 kg of CO_2 emissions in a year that is a 22% saving for Kilyos campus.

Fig. 2 compares the effects of using these three different objective functions on the resulting CO_2 savings. For each budget level, the optimization problem is solved by using maximizing CO_2 savings, financial savings, and energy savings as the main objective function.

Fig. 2 shows that maximizing the financial savings and maximizing the CO_2 savings give almost the same results in terms of the realized CO_2 emissions. However, when maximizing the

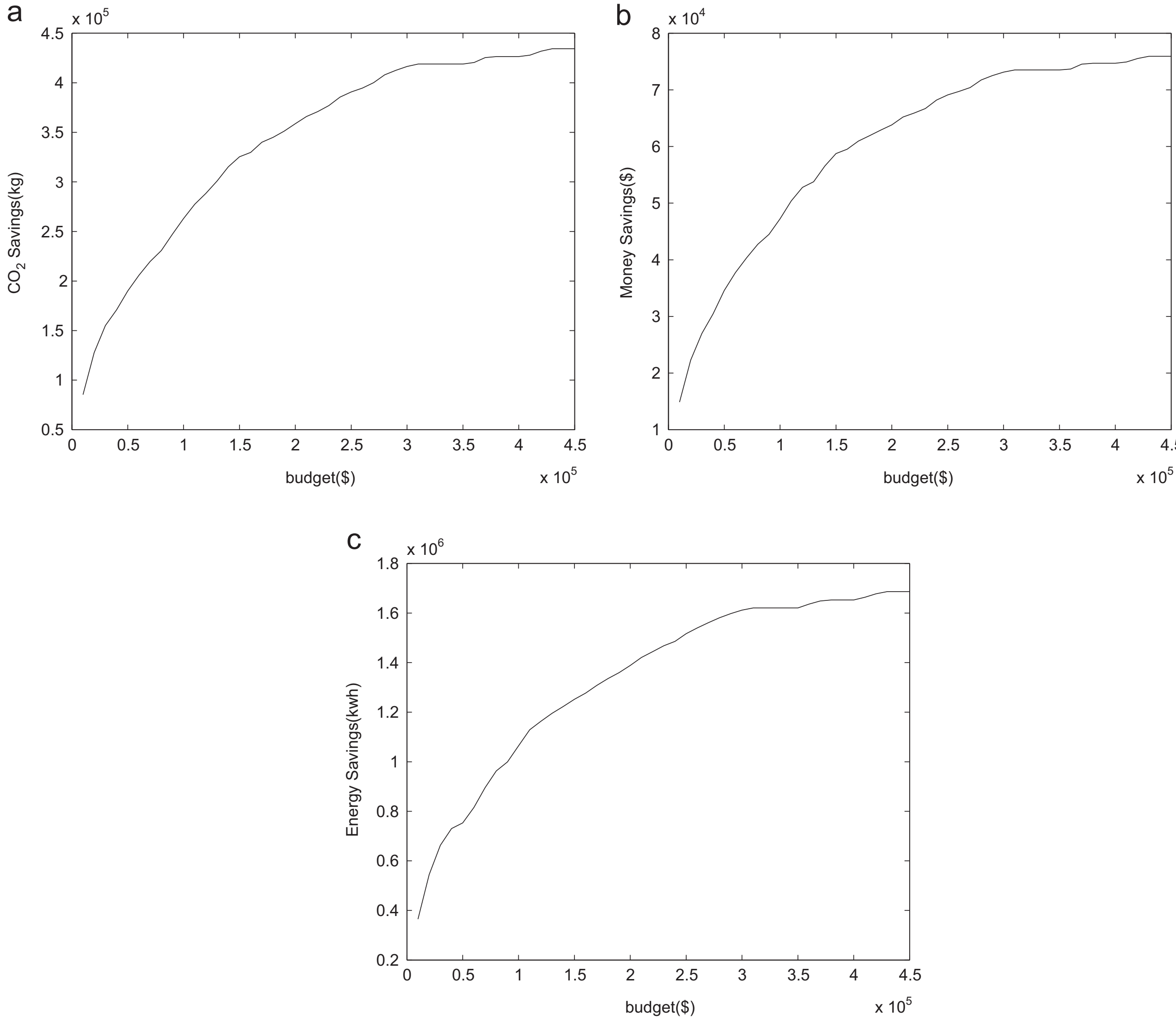

Fig. 1. Optimal results for different budget levels (B) when the objective is maximizing the CO_2, financial, or energy savings.

energy savings is used as the objective function, the realized CO_2 saving is lower than the CO_2 saving that is realized by using maximizing CO_2 or financial savings. This is due to using energy saving technologies that reduce the energy by decreasing the usage of natural gas or electricity as shown in Table 2. Although the same level of energy can be saved, the CO_2 emissions and energy costs are different.

The case analyzed in this study shows that the results of using maximizing the reductions in CO_2 emissions and maximizing the financial and energy savings as the objective function are very close to each other for the single-period case. As a result, maximizing financial savings can be used as the main objective function in the planning process without compromising the objective of achieving energy and environmental benefits for this project for the single period case. This observation holds only for the solution of the single period model. For the multi-period case, using different objective functions yields significantly different results. For example, if the objective is maximizing the financial benefits, energy-saving technologies that have an annual energy cost saving that is lower than the interest rate that can be obtained with the cost of these technologies will never be selected. However, these technologies will be selected if the objective is maximizing the reductions in CO_2 emissions or maximizing the energy savings. The effects of using different objective functions for the multi-period technology selection method are investigated in the next part.

4.2. *Magnitude of benefits of using a multi-period technology selection method*

We now focus on multi-period optimization to select energy saving technologies to maximize CO_2 and financial savings and quantify the savings that are achieved by using the multi-period approach over the single-period optimization by using the model of the Kilyos Campus. To compare the results of multi-period and single-period problems, energy saving technologies that are invested at the first period are assumed to yield the same savings during the planning horizon. Accordingly, the results for the reductions in CO_2 savings obtained from the single-period problem are multiplied with the planning horizon T. Similarly, the energy cost saving obtained from the single-period model is repeated for T periods and the net present value is determined from the resulting cash flow.

4.2.1. Focusing on CO_2 savings

Fig. 3 shows how much reduction in CO_2 emissions will be achieved when multi-period and single-period optimization methods are used to maximize the CO_2 savings for different initial budgets. As the figure shows, the multi-period optimization method yields substantially higher savings for the same budget. For example, an initial budget of 10,000$ brings a saving of close to 3.25 Million kg of CO_2 emissions in a 10-year-period that corresponds to an annual saving of 325,000 kg per year (29.25% saving for Kilyos campus). This is almost the quadruple the saving that can be achieved with a single-period planning. The difference between the multi-period and single-period results is more pronounced for lower initial budgets and for longer planning horizons.

Fig. 4 gives the ratio of the savings obtained by using the multi-period planning to the savings obtained by using the single-period planning method. For each budget level, the maximum CO_2 reductions are determined by solving the single and multi-period problems. Then the ratio of the multi-period solution to the single-period solution that is repeated for the length of the planning period is calculated and shown on the figure. For example, following the example in Fig. 3(a), it is possible to reduce CO_2 emissions by 3.25 Million kg in a 10-year period. A single-period approach would yield a reduction of 85,378 kg annually. Comparing the reductions in a 10-year-period shows that the multi-period approach yields 3.82 times more reduction compared to the single-period planning. The solution of the multi-period problem shows that starting with a low initial budget, a number of technologies are selected first, and then the accumulated future financial savings are used to invest in other technologies. Therefore, as the planning horizon gets longer, sufficient savings are accumulated to invest more and more technologies when a multi-period planning period is used. For higher initial budgets, the difference is lower since the majority of the technologies can be invested initially when single- and multi-period problems are solved. Therefore the relative advantage of the multi-period planning method is lower for higher initial budget levels.

Fig. 4 shows that the ratio of savings achieved by using multi-period model to that of single-period model approaches to 1.5 instead of 1, that might be expected, as the budget increases. The reason for this result is the envelope insulation retrofit technology (Table 3) that can only be chosen among three alternative for each building. When the multi-period planning is used, it is possible to invest in the envelope insulation retrofit options (4 cm, 5 cm and 6 cm) at different times. However, when

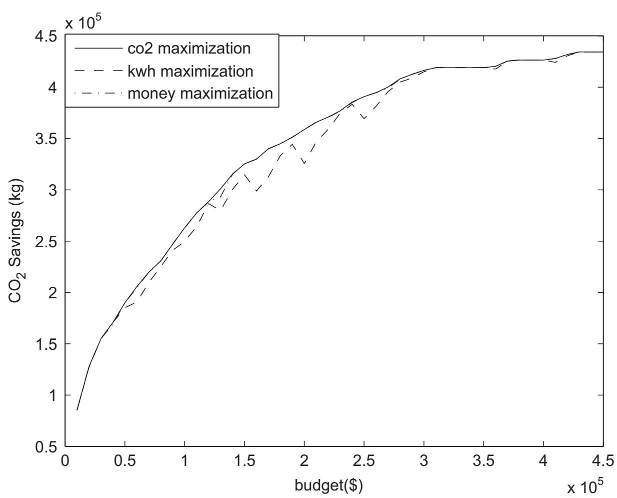

Fig. 2. CO_2 savings for different budget levels (B) when the objective is maximizing the CO_2, financial, or energy savings.

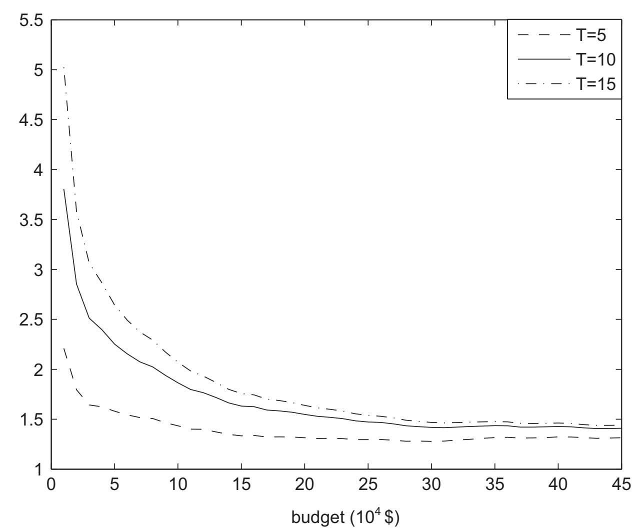

Fig. 4. The ratio of CO_2 savings obtained by using multi-period optimization to single-period optimization for different budget levels (B) with an objective of maximizing CO_2 savings.

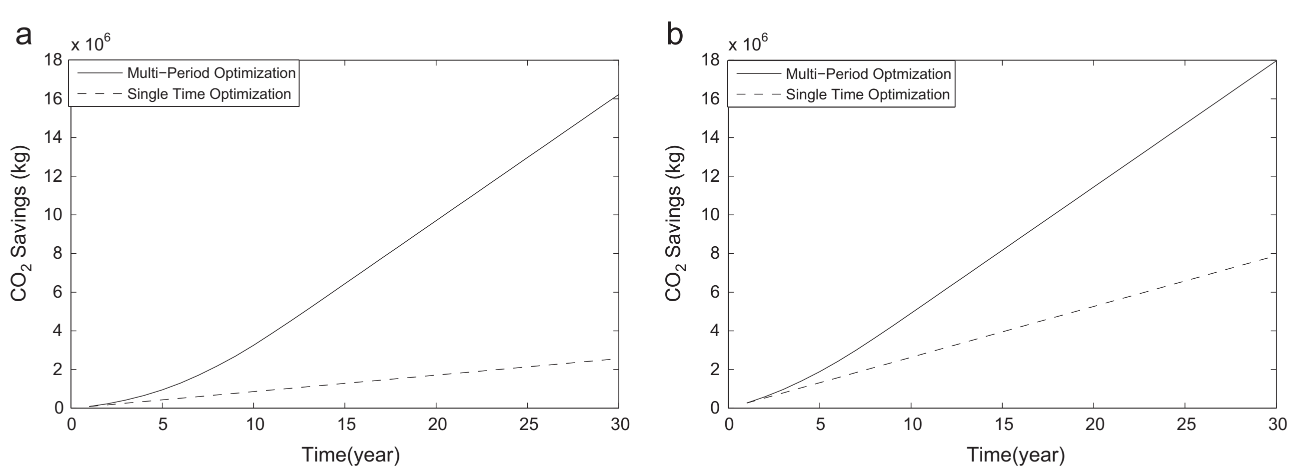

Fig. 3. The CO_2 savings obtained by using single- and multi-period optimization to maximize CO_2 savings for different budget levels (B). (a) $B = \$10,000$ and (b) $B = \$100,000$.

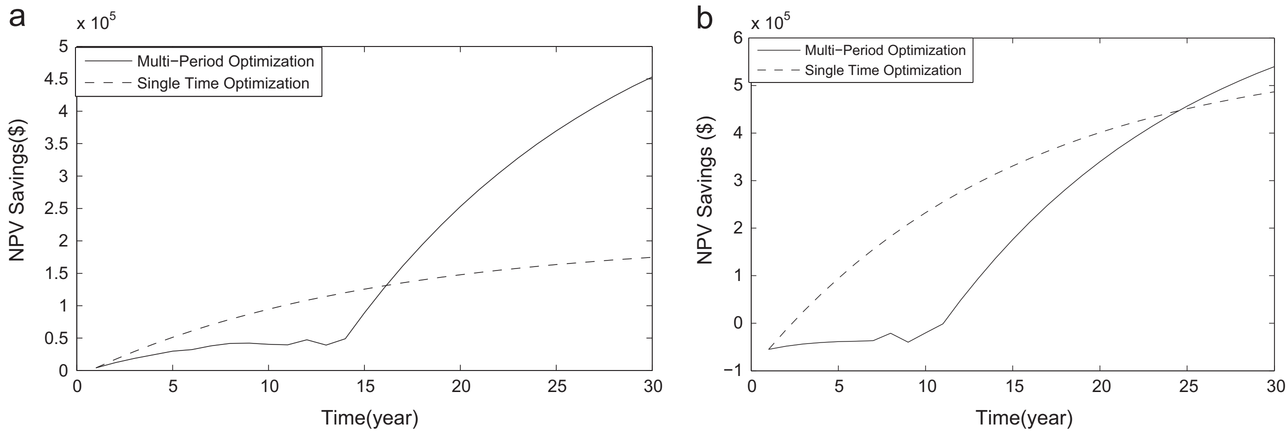

Fig. 5. The NPV savings obtained by using single- and multi-period optimization to maximize CO_2 savings for different budget levels (B). (a) $B = \$10,000$ and (b) $B = \$100,000$.

the single-period planning is used, only one envelope insulation option can be selected.

Fig. 5 shows the comparison of the net present values of the financial gains achieved when single- and multi-period optimization problems are used to maximize the savings in CO_2 emissions. Since the objective of the multi-period optimization problem is maximizing CO_2 savings, the maximum number of investments is selected when the cash flow is available without considering the short-term NPV effects. Because of this, the NPV can be negative for the initial part of the planning horizon.

The NPV curves in Fig. 5 appear to have a break point where they start increasing rapidly after staying stable at different times for different initial budgets, e.g. at $t=13$ when $B = \$10,000$ in Fig. 5(a), or at $t=9$ when $B = \$100,000$ in Fig. 5(b). This is due to the time period required to accumulate savings to invest in technologies that have higher investment costs. When the necessary money is accumulated to invest in these technologies, substantial savings are achieved in the remaining part of the planning horizon.

Fig. 6 gives the ratio of the net present value of the energy cost savings obtained by using the multi-period planning method to the net present value of the savings obtained by using the single-period planning when the objective function is maximizing CO_2 savings for different planning horizons and different initial budgets.

The multi-period planning optimization where the objective is maximizing the CO_2 emissions gives higher NPV compared to the single-period planning when the initial budget is low. However, it is possible to achieve a higher NPV with the single-period optimization with a CO_2 saving objective compared to the multi-period optimization for higher initial budgets. This is due to the optimal solution of the multi-period optimization problem that involves accumulating money first in earlier periods to invest in later time periods. In the next section, we show that when the objective is maximizing the financial savings, the multi-period optimization outperforms the single-period optimization in terms of NPV savings.

4.2.2. *Focusing on financial savings*

In the preceding section, the comparison was made for the single- and multi-period problems where the objective function was maximizing the CO_2 emissions. In this part, we focus on planning problems where the objective is maximizing the financial savings.

Fig. 7 gives the comparison of the NPVs when the multi-period optimization problem is solved with the objective of maximizing the savings in CO_2 emissions and the NPVs when the multi-period problem is solved with the objective of maximizing the NPV for a given budget. As expected, the multi-period optimization with the objective of maximizing the NPV gives higher financial savings compared to the case where the objective is maximizing the CO_2 savings.

Fig. 8 gives the ratio of the net present value obtained by using the multi-period planning method to the net present value obtained by using the single-period planning when the objective function is maximizing the net present value for different planning horizons and different initial budgets. For each budget level and planning horizon, both the multi-period and single-period problems are solved with the objective of maximizing the net present value. Fig. 8 gives the ratio of the values of the optimal net present values for single- and multi-period cases.

The multi-period planning increases the financial savings substantially. For example, when the single-period planning approach is used, an investor can realize an energy cost saving of $47,238 with an initial budget of $100,000 by investing in energy saving technologies as shown in Fig. 1(b). In a 15-year period, assuming that the investor collects the same saving every year with its initial investment of 100,000, the net present value of this investment is $330,240 with $r=7\%$. The multi-period planning approach yields a net present value of $403,241 that is 22% improvement over the single-period approach for the same initial budget.

When the objective is maximizing the net present value in a multi-period optimization problem, it is possible to have a plan that dictates accumulating cash to collect interest rather than investing in a technology. This happens especially when the initial budget is high. When the initial budget is high enough to invest in many technologies, all the possible technologies are invested according to the solution of the single-period planning problem to maximize the return in 1 year. However, when the multi-period approach is used, a technology may not be selected if the marginal financial return on the added technology is lower than the return from the financial markets.

Compared to high investment costs for building new energy generators, we show that energy efficiency of existing buildings can be increased by using a much lower investment. Continuing with the same example, an initial budget of $100,000 invested in technologies selected by the multi-period model presented in this study brings $403,240 NPV, reduces the CO_2 emissions by 8 tons, and yields an energy saving of 32 million kWh in 15 years, or approximately 2.13 million kWh per year. The investment cost of a hydroelectric power plant recently built in Turkey that will produce 144 million kWh of energy in a year was $96 million. If the same investment was directed to investing in improving energy efficiency of existing buildings, similar to Kilyos campus, it will allow undertaking 960 projects that will be invested at a level of $100,000. Therefore, the total energy saving from all the projects that use the investment of a single hydroelectric plant will be 2045 million kWh. This is equivalent to the energy that will be produced by 14 hydroelectric plants. In other words, investing in energy efficiency measures of existing buildings will bring 14 times more energy compared to building hydroelectric plants. Given that there are close 14 million residential buildings in Turkey and 92% of them do not comply with the energy efficiency standards, it is possible to implement investments in energy efficiency measures at a large scale.

4.3. Feasibility of the business plan to offer energy saving technologies as a service

For a business plan to offer energy saving technologies as a service, the financial viability of the service is crucial to attract firms that will offer this service to its customers. The models developed in Section 2.3 can be used to understand the interplay between the contact duration, financial return, and the CO_2 savings that will be achieved. In this section, we focus on the minimum profit requirement and the profit sharing with the customer and use the data of the case study to quantify the effects.

4.3.1. Minimum profit requirement

As described in Section 2.3.2, the trade-off between achieving financial savings and CO_2 savings can be managed by solving an optimization problem where the objective is maximizing the CO_2 savings subject to a minimum desired profit that is expressed as a multiple ρ of the initial budget. The profit rate ρ indicates the desired return on the initial investment. The formulation given as Model M13 in Table 1 is solved for Boğaziçi Kilyos Campus to analyze the effects of ρ on the CO_2 savings.

Fig. 9 shows the NPV savings for different levels of ρ for two cases with different initial budget levels and contract durations. Fig. 9 shows that when the desired profit rate ρ increases the CO_2 emission that will be achieved decreases. This is due to giving more priority to technologies that yield higher financial savings rather than CO_2 savings as ρ increases.

For a low initial budget, the model yields substantial financial benefits while maximizing the savings in CO_2 emissions. Fig. 9 (a) shows that for an initial budget of $10,000, it is possible to get a ten-fold return in 10 years, that is equivalent to 26% annual return,

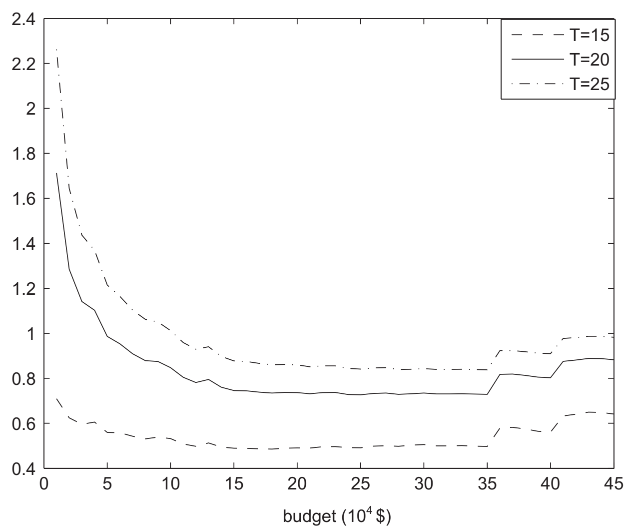

Fig. 6. The ratio of NPV savings obtained by using multi-period optimization to single-period optimization for different budget levels (B) with an objective of maximizing CO_2 savings.

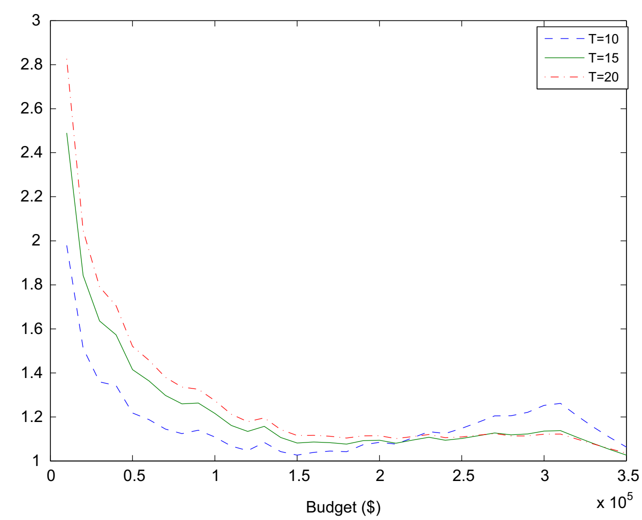

Fig. 8. The ratio of NPV obtained by using multi-period optimization to single-period optimization for different budget levels (B) with the objective of maximizing NPV.

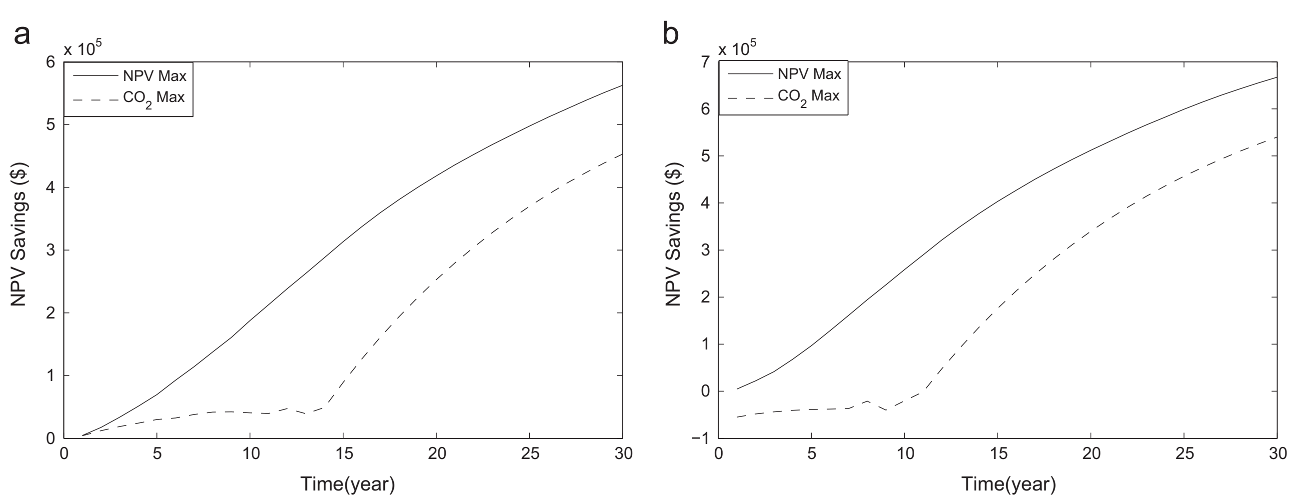

Fig. 7. The NPV savings that will be achieved for multi-period planning problems with the objectives of maximizing NPV and CO_2 savings for different budget levels (B). (a) $B = \$10,000$ and (b) $B = \$100,000$.

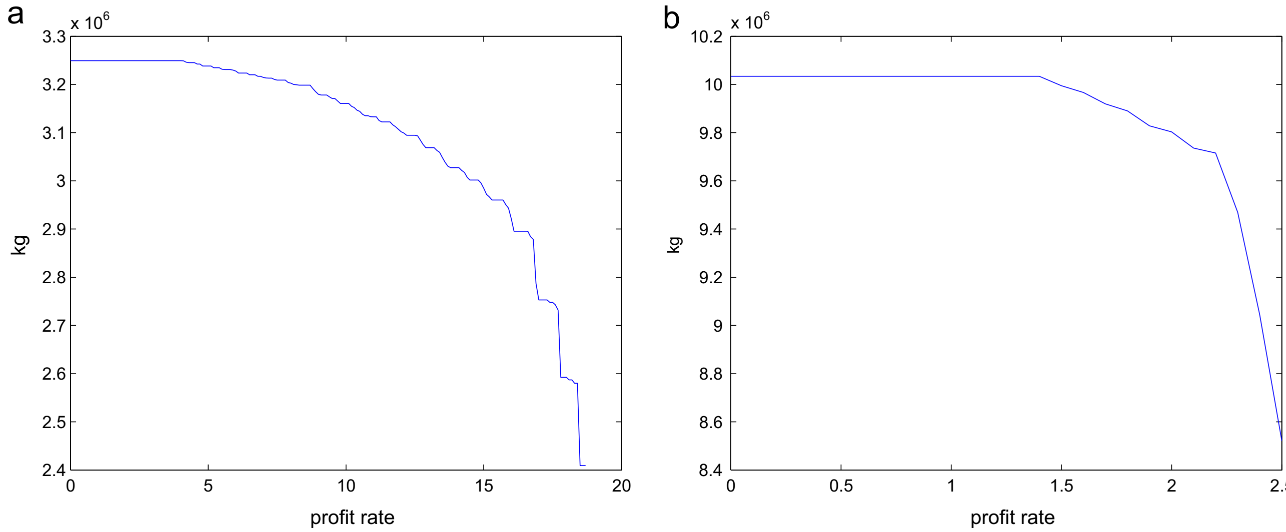

Fig. 9. The total saving in CO_2 emission obtained by using multi-period optimization model with CO_2 saving objective subject to achieving a minimum level of NPV for different profit rates ρ. (a) $B=\$10,000$, $T=10$ and (b) $B=\$180,000$, $T=17$.

with only 2% decrease in the maximum possible CO_2 savings of 3.25 ton per year to 3.185 ton per year when $\rho=10$. From the service provider point of view, this may suggest that a service provider may increase its financial return while providing the steepest increase in the CO_2 savings by using its initial cash invested in a number of customers in smaller amounts rather than investing all of it in one project. This is in line with the law of diminishing returns and also provides the highest environmental benefit for each dollar invested. However, the customers may expect higher savings in CO_2 or energy expenditures in absolute terms. This issue should be negotiated between the service provider and its customer.

4.3.2. Sharing profit between the company and its customer

As described in Section 2.3, a company may offer energy saving technologies as a service to its customers. In this arrangement, the service provider and the customer shares the savings in energy expenditures: the customer receives Δ of the savings in energy expenditures every year while the service provider uses the remaining $1-\Delta$ part to invest in energy-saving technologies in such a way that it maximizes its own financial benefit to cover its initial investment and also provide a financial benefit. Δ is referred as the saving ratio.

Fig. 10 shows the total saving in CO_2 emissions when a service provider uses the multi-period planning problem to maximize the CO_2 savings to select the energy saving technologies for different levels of Δ. As Δ increases, the customer benefits more and the service provider receives a smaller part of the savings. As a result, the number of technologies that are invested in decreases as well as the total savings in CO_2 emissions.

Fig. 11 shows the NPV of the service provider when the service provider uses the multi-period planning problem to maximize the NPV savings to select the energy saving technologies for different levels of Δ. Similar to the previous case, as Δ increases, the customer benefits more and the service provider receives a smaller part of the savings. Consequently, the number of technologies that are invested in decreases and the NPV of the service provider decreases.

Fig. 11 shows that offering energy saving technologies is a lucrative investment for the service provider. Even when 50% of the energy saving is given to the customer, the return on an initial investment of $10,000 is $59,000 with a 10-year contract and close

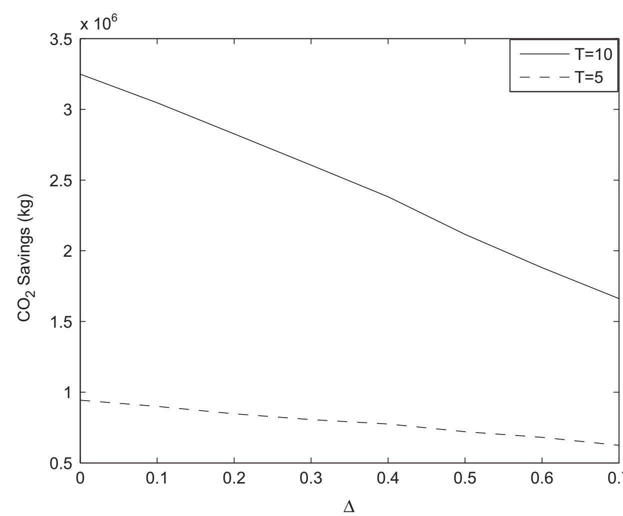

Fig. 10. The saving in CO_2 emissions for a multi-period planning problem to maximize CO_2 savings for different values of saving ratio Δ ($B=\$10,000$, $T=5,10$).

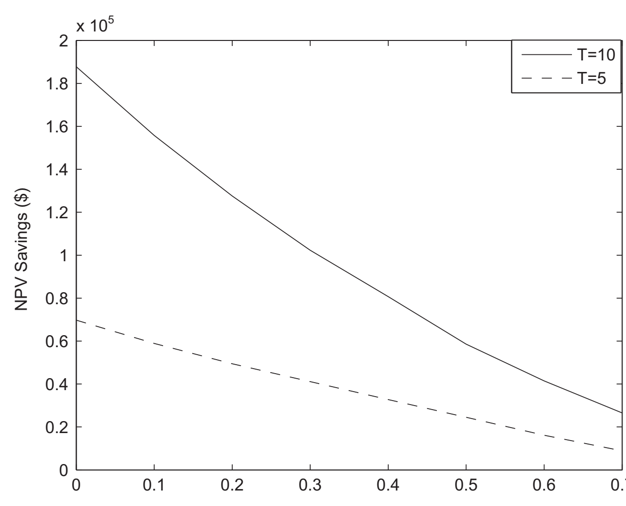

Fig. 11. The service providers NPV for a multi-period planning problem to maximize NPV for different values of saving ratio Δ ($B=\$10,000$, $T=5,10$).

to $24,650 with a 5-year contract. With a contract of 10-years, the net present value of the total energy cost saving provided to the customer is around $69,000 that is equal to the return of the service provider including its initial investment. The customer receives this financial saving without any investment. As a result of this arrangement, the CO_2 emission is reduced around 2.11 Million kg in a 10-year-period. This is a substantial benefit for the environment, for the customer, and also for the service provider.

5. Conclusions

Energy use in buildings is responsible for one-third of total global energy consumption and total global CO_2 emissions. Increasing the energy efficiency in existing buildings is an effective way to save energy and decrease CO_2 emissions.

This study presents a Mixed Integer Programming algorithm to select the energy saving technologies among all the available ones in order to maximize the environmental or financial savings in single- and multi-period cases. By using the data collected and measured for Boğaziçi University Kilyos Campus, we focus on three issues: the effects of using financial savings, energy savings, or CO_2 savings as the objective function of the optimization problem; the advantages of using a multi-period technology selection method over the single-period selection of technologies; the benefits of offering energy saving technologies as a service for the service provider, its customers, and also for the environment.

We determined that using environmental savings, expressed in terms of reductions in CO_2 emissions or financial savings, expressed in terms of the net present value as the objective function is preferable to using energy savings. Furthermore, for the single-period model, using maximization of the reductions in CO_2 emissions or maximization of the financial savings as the objective function give almost the same results as using the CO_2 savings as the main objective. Therefore, there is no dichotomy between using environmental or financial benefit as the main objective in the planning problem. For the multi-period problem, the results differ depending on the planning horizon. However, if a decision maker is concerned with the total savings that will be achieved at the end of the contract period, using CO_2 savings or the cost savings as the objective function yields substantial environmental and financial savings. As expected, using the appropriate objective function for a performance yields a higher return for that performance measure. The results show that significant financial and environmental benefits can be achieved by relatively low investment levels. Furthermore, using the multi-period planning improves the net present value substantially compared to using the single-period planning as a result of accumulating financial gains to invest in other technologies to improve the net present value.

This study proposes a joint solution that uses architectural, engineering, financial and operations research approaches to the solution of increasing energy efficiency. As a result, we show that offering energy saving technologies as a service is a *win–win–win* situation for the service provider, its customer, and for the environment. The decision model presented in this study provides the framework to select the right technologies to maximize the desired objective function subject to budgetary and other logical constraints.

Improving energy efficiency of buildings can also be considered as a way of contributing to the future energy needs of countries. Countries with high growth rates face substantial demand for energy investments. Energy that can be saved in existing buildings can decrease the need for future energy investments. The initial investment can be made by service providers that will offer the energy efficiency measures as a service to its customers and make the investment on behalf of the building owners or developers in exchange of sharing the future energy cost savings for a predetermined period. We show that this business model brings substantial financial benefits and therefore may attract investors to offer energy saving technologies as a service. At the end, this engagement accelerates the installation of energy saving technologies to existing buildings; and therefore increases energy efficiency and lowers CO_2 emissions. The model presented in this study can be used to select the contract parameters in the right way to provide benefits to all the involved parties in such a business plan.

This study can be extended to study the business model from the service provider point of view. Energy price fluctuations and weather fluctuations introduce risks to a service provider that will make investments in energy saving technologies. In order to mitigate this risk, third party financing can be considered for the sharing risk between the customer and the company. Furthermore, this study analyzes investing in a single site. Selecting the right amount of investment in different sites for a given total budget, and selecting the energy saving technologies for each project with the allocated budget for that site can bring even higher substantial financial gains and environmental gains. These extensions are left for future research.

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