Large-scale building energy efficiency retrofit: Concept, model and control

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Abstract

Building energy efficiency retrofit (BEER) projects are initiated in many nations and regions over the world. Existing studies of BEER focus on modeling and planning based on one building and one year period of retrofitting, which cannot be applied to certain large BEER projects with multiple buildings and multi-year retrofit. In this paper, the large-scale BEER problem is defined in a general time-building-technology (TBT) framework, which fits essential requirements of real-world projects. The large-scale BEER is newly studied in the control approach rather than the optimization approach commonly used before. Optimal control is proposed to design optimal retrofitting strategy in terms of maximal energy savings and maximal net present value (NPV). The designed strategy is dynamically changing on dimensions of time, building and technology. The TBT framework and the optimal control approach are verified in a large BEER project, and results indicate that promising performance of energy and cost savings can be achieved in the general TBT framework.

Keywords: building retrofit, energy efficiency, optimal planning, net present value, control

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1. Introduction

Energy demand in the building sector is continuously increasing due to the high growth of population and buildings. Now approximately 40% of global energy consumption is attributed to residential, office and commercial buildings. As there are a large number of old buildings equipped with out-of-date facilities, whose operations may be also inefficiently scheduled, it has great potential to decelerate the increasing rate of energy demand or possibly reduce total demand in the building sector [1]. For this purpose, an intuitive but costly way to improve existing buildings is to replace them with new green buildings. Due to the investment limit, the replacement rate is only around 1.0-3.0% per year. The most popular way to improve energy performance is building energy efficiency retrofit (BEER) [2, 3], as the retrofit can provide promising energy savings with less investment than the replacement. The energy efficiency retrofit also plays important roles in reducing fossil fuel consumption, reducing greenhouse gas emission and improving building market value.

From the start of this century, many policies and projects have been initiated all over the world to improve energy efficiency of building. In the United States, governments have established retrofit initiatives and programs to promote energy savings in the building sector. The "Better Building Initiative" has a target of reducing 20% energy consumption in commercial buildings by 2020 through cost-effective retrofit interventions [4]. Under this initiative, about 200 organizations have joined for improving energy efficiency of 3 billion square feet of floor area. In Europe, the Energy Performance of Buildings Directive (EPBD) [5] and the Energy Efficiency Directive [6] are published to encourage member states to identify policies to stimulate deep renovation and retrofit in a cost-effective way. In Germany, the government is committed to reducing the primary energy demand of buildings by 80% by 2050 [3]. In Australia, the Commercial Building Disclosure (CBD) program has been proposed to promote energy efficiency and sufficient budget has been invested to building retrofit [7].

A building with complicated outdoor environment is a complex system with many sub-systems, such as lighting, water, heating, cooling, ventilation and envelop. Every sub-system has great effects on the total performance of energy efficiency, and the interaction between sub-systems also has close relation with energy savings [8, 9]. Besides energy efficiency, many other concerns, including technical, technological, ecological, social, aesthetical and economic concerns, have to be balanced in building refurbishment. Therefore, a thorough building refurbishment is quite difficult to undertake, as it may contradict certain concerns aforementioned. Building energy efficiency retrofit refers to changing existing facilities with innovative and efficient technologies in terms of building envelope (wall, roof or windows), energy systems (heating, cooling or domestic hot water), lighting [10], and other electrical appliances. The main purpose of BEER is to achieve energy savings, while certain requirements are still satisfied. In related work of BEER, researchers mainly focused on modeling and planning for providing stakeholders guidelines of real-world projects [2, 11]. Researchers have proposed multi-criteria BEER models for decision making and performance assessing [12, 13], in which optimal solutions of BEER are expected to answer the following three questions.

- Which existing facilities are selected for refurbishment?
- How many interventions are required to retrofit existing facilities in each category with the limited budget?
- Which alternative interventions are employed if there are multiple alternative candidates in each category?

Firstly, the selection of alternative interventions is usually determined by the multi-objective optimization approach, in which the target problem usually belongs to a binary programming problem [13, 14, 15, 16]. In [13], retrofitting cost and building load coefficient are optimized to determine the types of window, insulation material, and the layers of insulation. In [14], the conflicting objectives, i.e., retrofitting cost and energy savings, are optimized to select proper window, wall, roof and solar collector. In [15], the prioritization of energy efficiency measures is studied for the residential and small commercial buildings, in which the alternative choices of envelop, energy system, lighting system, and electrical appliances are evaluated. In [16], financial and environmental benefits are optimized over single year and multi-year scales.

Secondly, the investment decision has been evaluated with the multi-objective optimization approach, in which the target problem is formulated as an integer programming problem [17]. In [17], the authors aim to find the optimal number of interventions in each category for maximizing energy savings and minimizing payback period with genetic algorithm. With the limited budget, only certain kinds of interventions can be selected with good balance between economy and efficiency concerns. The sensitivity analysis is also performed by analyzing the influences caused by the auditing error, specification error, and other uncertain parameters.

Thirdly, the optimal combination of interventions (type and number) is generally a mix-integer programming problem if multiple alternative candidates are considered. In [18, 19], optimal retrofitting plans with multiple alternative candidates have been evaluated based on the life-cycle cost analysis (LCCA), in which the retrofitted interventions suffer from performance decay, such as facility deterioration and failure. In [18], retrofitting plan obtained is optimal with respect to energy savings, net present value (NPV) and payback period over the life cycle. A rule-based maintenance plan and the fixed budget are given in the optimization of these three objectives. To optimize the maintenance plan that has close effects on the retrofitting performance [20, 21], multi-objective evolutionary algorithm is employed to help decision makers select representative solutions among several Pareto optimal solutions [19]. The maintenance plan together with the retrofitting plan is scheduled in the optimization of budget, NPV, and payback period.

In all, most work on BEER has focused on studying a certain kind of representative building. As every building exhibits unique architectural, geographical, and operational characteristics, BEER modeling and planning must be rationally investigated for every individual building. For the large BEER project that includes two or more buildings with different characteristics, the overall model appears much more complicated rather than each individual model of each building, which has not been taken enough emphasis in the research society. However, large-scale BEER programs have been initiated by stakeholders or governments in many nations or regions to reduce energy consumption. Large-scale BEER programs in Kuwait have been evaluated in [22], and the authors have found that the establishment of these programs can provide significant economic and environmental benefits. In [23], the relevance of calibration in model-based analysis is examined among a set of decision-making situations for the large-scale BEER. Obviously, studies on the large-scale BEER are not systematic and sufficient, and there are many open issues like definition, modeling and planning. To our best knowledge, the definition, modeling and planning of the large-scale BEER is firstly studied in this paper to help decision makers design the right retrofitting strategy according to their preferences.

The contributions of this paper mainly include three aspects. Firstly, the large-scale BEER is defined in the proposed TBT framework, in which 3 dimensions of time, building and technology are essential factors of the large-scale BEER. Secondly, the large-scale BEER is modeled, and energy savings and NPV are expressed with respect to retrofitting decisions over years. Thirdly, the control approach is newly introduced to the large-scale BEER. Using the weighted sum method, different optimal trade-offs between two conflicting objectives (energy savings and NPV) can be found by the optimal control. A large building retrofit project is studied to verify the TBT framework and the optimal control approach. The optimal strategies that are dynamically changing on dimensions of time, building and technology can achieve maximal energy savings and NPV, respectively.

This paper is organized as follows. In Section 2, some previous studies on BEER are introduced. In Section 3, definition and model of large-scale BEER are given under the TBT framework. In Section 4, an optimal control approach is proposed to design optimal retrofitting strategies. In the approach, the large-scale BEER is regarded as a control system, and energy savings and NPV are regarded as control outputs to be maximized. In Section 5, experiments on a large BEER project are conducted to verify the TBT framework and the optimal control approach. This paper is concluded in the last section.

2. Previous works

In multi-criteria BEER models, several performance criteria have been considered for optimal design of retrofitting plans. These criteria usually cover concerns of energy efficiency, environmental friendliness, economy and human comfort. Specifically, stakeholders always expect to reduce building energy consumption, to reduce carbon and waste emission, to increase financial payback, and to increase human living comfort in the BEER projects. Two representative BEER models are introduced in this section, which can represent two typical categories, i.e., non-LCCA-based [13, 14, 15, 17] and LCCA-based [18, 19].

2.1. Model A

In [17], a multiple objective optimization model is formulated to help decision makers design an optimal investment plan of BEER. The problem studied is to decide optimal numbers of alternative facilities when the budget of retrofitting is limited. Annual energy savings and payback period of investment are considered as two objectives to be optimized. The annual energy savings and payback period are formulated as

$$\begin{cases} ES = \sum_{i=0}^{I} a_i x_i, \\ T_p = \frac{\sum_{i=1}^{n} b_i x_i}{\sum_{t=1}^{T} \sum_{i=1}^{n} a_i x_i c (1+r)^t / T}, \end{cases} \tag{1}$$

where $x = (x_1, x_2, ..., x_I)$ is the decision variable, and x_i represents the number of the ith type facility (I is the total number of types). a_i is the average annual energy savings of the ith type facility (kWh); b_i is the unit price of the ith type facility (\$); c is the electricity price (\$); r is the increasing rate of electricity price; T is the evaluation period (year) that is relatively long for achieving positive NPV. The first objective ES is the overall energy savings in a year in the post retrofitting period. The second objective T_p is the payback period calculated as the ratio of investment cost and average annual financial benefit. In this model, the retrofit planning is formulated as a minimization problem as

$$\begin{aligned} &\min \lambda_1 T_p - \lambda_2 ES, \\ &s.t. \begin{cases} 0 \le x_i \le l_i, i = 1, ..., I, \\ ES \ge \alpha, \\ \sum_{i=1}^{n} b_i x_i \le \beta, \end{cases} \end{aligned} \tag{2}$$

where λ_1 and λ_2 are positive weighting factors satisfying $\lambda_1 + \lambda_2 = 1$. l_i is the maximum number of the ith type facility experiencing retrofit; α is the energy saving target (kWh); β is the budget of investment (\$).

Note that facility decay and energy performance deterioration are neglected in Model A. In other words, energy saving and cash flow at each year are constant during the post-implementation period. Life-cycle cost, including operation cost and maintenance cost, has been neglected in Model A. Like Model A, other models introduced in [13, 14, 15] also belong to non-LCCA-based fold.

2.2. Model B

As the installed alternative interventions suffer from decay over time, the number of failed items or the extent of deterioration must grow over time if no maintenance carries out. Therefore, maintenance is required to ensure the stable performance of ongoing energy savings, although new maintenance cost is introduced over the life cycle.

In [18], besides retrofitting cost of initial year, maintenance cost over the life cycle has been considered in the BEER period. The decay of retrofitted facilities is assumed as a first-order Markov process, which means the population size at a certain year only related to the population size at the previous year. A multi-objective BEER model is then presented based on the life-cycle cost analysis. Multiple interventions are considered as retrofitting candidates for each type of existing facilities in this model. Besides energy savings and payback period, NPV is the third objective to be optimized. Assume that there are I types of existing facilities to be retrofitted, and J_i types of alternative interventions for the ith ($i = 1, 2, ..., I$) type facility. The jth type alternative intervention for retrofitting the ith type facility is simply called alternative (i, j). Let $x_i^j(j = 1, 2, ..., J_i)$ denote the number of items of the alternative intervention (i, j). Then energy savings and NPV can be formulated as

$$\begin{cases} ES = \sum_{t=0}^{T} \sum_{i=1}^{I} \sum_{j=1}^{J_i} a_i^j x_i^j(t), \\ NPV = \sum_{t=1}^{T} \frac{B(t)-C(t)}{(1+d)^t} - \sum_{i=1}^{I} \sum_{j=1}^{J_i} b_i^j x_i(0), \end{cases} \tag{3}$$

where T is the evaluated period (year), and $x_i^j(t)$ is the number of working items of the alternative intervention (i, j) at the tth year. It is obvious that $x_i^j(0)$ is the number of alternative intervention (i, j) in the initial retrofitting investment. a_i^j is the average annual energy savings (kWh), and b_i^j is the unit price ($). $B(t)$ represents the financial profit caused by energy savings at the tth year; $C(t)$ represents the maintenance cost at the tth year; d is the discount rate in the NPV calculation. The calculation of $B(t)$ and $C(t)$ omitted here can be referred from [18].

Note that $x_i^j(t)$ is time-varying due to facility decay and maintenance in Model B, while this value in Model A is considered as a constant over the evaluation period. The dynamic of $x_i^j(t)$ is expressed as

$$x_i^j(t+1) = \Delta(x_i^j(t)) + \sigma_i^j(t), \tag{4}$$

where $\Delta(\cdot)$ is a decreasing singular function, namely the decay model mentioned in [18, 24]. $\sigma_i^j(t)$ is the number of failed alternative intervention (i, j) experiencing maintenance at the tth year. In Model B, the discounted payback period T_p is simply defined as the time point when zero NPV appears. The optimal planning problem is formulated as optimization of the weighted sum of ES, NPV and T_p, while constraints of item numbers, energy savings, discounted payback period, and initial budget have to be satisfied as

$$\begin{aligned} &\min -\lambda_1 ES - \lambda_2 NPV + \lambda_3 T_p, \\ &s.t. \begin{cases} \sum_{j=1}^{J_i} x_i^j(0) \leq q_i, i = 1, 2, ..., I, \\ ES \geq \alpha, \\ \sum_{i=1}^{I} \sum_{j=1}^{J_i} b_i^j x_i(0) \leq \beta, \\ T_p \leq T_0, \end{cases} \end{aligned} \tag{5}$$

where λ_1, λ_2 and λ_3 are positive weighting factors satisfying $\lambda_1 + \lambda_2 + \lambda_3 = 1$. q_i is the total amount of items for the ith type facility; α is the energy saving target of project (kWh); β is the budget limit of project ($); T_0 is the expected payback period of project (year). The energy saving target is usually a percentage of total energy consumption (typically 10%). In Model B, the maintenance plan is that in every two years all failed interventions are fixed or replaced in their study. Therefore, the decision variable of optimization is the retrofitting plan at the initial year, and the optimal retrofitting strategy is expected to minimize the objective function with the fixed maintenance plan.

Besides retrofitting plan, maintenance plan is also optimized in the decision making in our recent study [19]. Pareto optimal solutions in terms of retrofit cost, energy savings and NPV are obtained with accuracy and diversity. Some representative strategies can cover possible preferences of decision makers. Both retrofitting and maintenance costs are minimized to design the optimal retrofitting and maintenance plans over the life cycle. Unlike non-LCCA models, LCCA models [18, 19] are proposed to evaluate the long-term performance improvement with time-varying system dynamics.

In summary, for existing models retrofit is usually conducted at the beginning of investment period. The benefits, like energy savings and NPV, are then evaluated for each year. In the non-LCCA-based models, these benefits are static for each year; in the LCCA-based models, these values are dynamically changing due to decay and maintenance. No retrofit is planned during the whole period in either non-LCCA-based or LCCA-based models. Moreover, these models are built for each single building, and each model is verified by the case studies of one representative building.

3. Large-scale BEER

In certain government or regional projects, a great number of facilities or buildings are required to implement BEER in one project. In this case, initial budget is often insufficient to cover the whole project and the following budget is allotted in several times. Unlike previous studies, in which one building is involved in BEER and retrofit is conducted only in the initial year, in this study long-term retrofit will be conducted in multiple times over the project period. A large-scale BEER model is proposed to fit requirements of such large projects. The effects of long-term retrofit to energy and economy will be evaluated in the large-scale BEER.

3.1. Definition

In fact, many large projects often include more than one building, which may have heterogeneous characteristics, such as different environment and energy consumption patterns. The implementation period is possibly more than one year, during which cost savings or rebates in one year can be invested to retrofit more facilities in the following years. Therefore, it is necessary to give a comprehensive definition of the large-scale BEER to fit scope changes.

In multi-year investment, inflation may have great negative effect on the earned cost savings, although there also exists certain interest. For reducing the inflation effect, the cost savings at the early stage are invested in the building retrofit project to earn more energy savings as well as the equivalent cost savings. In practice, three new questions are arisen over the life cycle as the scope is changed in these large-scale BEER projects.

(1) What is the priority list of building for retrofitting among multiple buildings? These buildings, including office, commercial or residential buildings, are not homogeneous with different characteristics. The differences lie in their energy consumptions, distribution of existing facilities, and their external environments (due to location and orientation). Only a portion of buildings in a large project is experiencing retrofit at the first year. If only one building is simply assigned to be retrofitted in one year, project advisors must decide a priority list of buildings for each year that can maximize their benefits.

(2) What is the priority list of technology for retrofitting in a specific building? Several technologies, such as lighting, water heating and air conditioner, are usually employed to provide building services that contribute most energy consumption. The type of technologies is a great number in the large-scale BEER. Retrofitting facilities belonging to each technology will require different budget and earn different energy savings. Cost savings are also varying between technologies due to different energy savings and consumption patterns. Some technologies can be retrofitted to achieve great energy savings, but the associated investment is also large. Project advisors must choose the most economic technology for retrofitting at the first stage. If only one technology is simply assigned to be retrofitted in one year, people also have to decide a priority list of technologies for each building.

(3) How will project advisors design the best investment plan to maximize financial benefit over years? Investing some money at the first years can achieve more energy savings and cost savings than investing the same amount of money at the later years. For the last years of period, investment can only achieve limited energy savings, so investment may suffer from risk of loss. As a good investment plan, more investment should be taken in the first years, less investment should be taken in the later years, and no investment should be taken in the last years.

The scope of the large-scale BEER must be extended to response these newly questions arisen for covering three essential factors, i.e., incremental investment, building characteristics, distribution of multiple technologies. In this paper, the large-scale BEER can be generally expressed into 3 dimensions, i.e., time, building and technology, as shown in Figure 1. The t-axis represents time (in terms of year or season), and incremental investment of each year will be considered on the time dimension. The j-axis represents technologies (in terms of different building services), and different technologies will be put different significance of retrofitting on the technology dimension. The k-axis represents type of buildings, and different buildings are retrofitted at different stages on the building dimension. The proposed framework is called the time-building-technology (TBT) framework of large-scale BEER problems.

In the TBT framework, the project evaluation period is usually from 3 to 10 years. The technologies for retrofitting can be usually classified into lighting, water heating, air-conditioner, plug-in device (such as TV, computer, stereo and projector) and envelope insulation (walls, roofs and windows). According to functions, existing buildings can be usually classified into residential, commercial, industrial, office, hospital and school. The optimal solution of the large-scale BEER is expected to guide retrofitting among buildings and technologies for each year. It can be noted that the TBT framework can generalize most previous work of BEER. For example, Model A and others mentioned

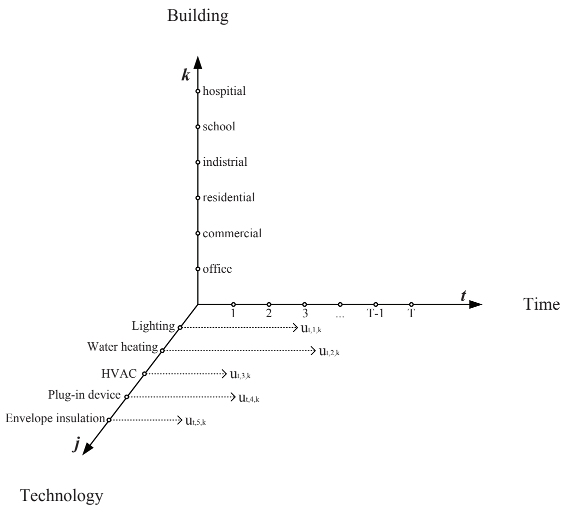

Figure 1: Three factors considered in the proposed time-building-technology (TBT) framework

in [13, 14, 15, 17] belong to the technology dimension, in which the retrofitting plan is designed for one building at the first year; Model B belongs to the plane crossing technology and time without considering multiple buildings.

3.2. Model

Compared with the models introduced before, the large-scale BEER model appears several new characteristics. Firstly, the retrofit period is more than one year, during which financial investment is given in multiple times for each year. Secondly, a large number of facilities are involved in the project, in which several building stocks are experiencing retrofit. Due to new characteristics, energy savings ES can be formulated as

$$\begin{aligned} ES(t) &= \textstyle\sum_{\tau=0}^{t-1} \sum_{h=1}^{H} \sum_{i=1}^{I_h} \sum_{j=1}^{J_{h,i}} a_{h,i}^{j} \cdot u_{h,i}^{j}(\tau) \\ &= \textstyle\sum_{h=1}^{H} \sum_{i=1}^{I_h} \sum_{j=1}^{J_{h,i}} a_{h,i}^{j} \cdot x_{h,i}^{j}(t), \end{aligned} \tag{6}$$

where $t = 1, ..., T$ and H is the number of buildings in the project; I_h is the total types of existing facilities in the hth building; $J_{h,i}$ is the types of alternative facilities for retrofitting the ith type facility in the hth building. In this paper, the notation (h, i, j) is used to represent the jth type alternative intervention for retrofitting the ith type existing facility in the hth building. $u_{h,i}^{j}(t)$ is the number of retrofitted items of the alternative intervention (h, i, j) at the tth year; $a_{h,i}^{j}$ is the average annual energy savings of the alternative intervention (h, i, j). $x_{h,i}^{j}(t)$ is the cumulative number of retrofitted items over t years, i.e., $x_{h,i}^{j}(0) = 0$ and $x_{h,i}^{j}(t) = \sum_{\tau=0}^{t-1} u_{h,i}^{j}(\tau)$. Note that $ES(0) = 0$ here.

Cash flow CF can be formulated as

$$CF(t) = f(x(t)) - \sum_{h=1}^{H} \sum_{i=1}^{I_h} \sum_{j=1}^{J_{h,i}} b_{h,i}^{j} \cdot u_{h,i}^{j}(t) - g(u(t)), \tag{7}$$

where $b_{h,i}^{j}$ is the unit price of the alternative intervention (h, i, j). $u(t) = (u_{1,1}^{1}(t), ..., u_{1,1}^{J_{1,1}}(t), ..., u_{H,I_H}^{J_{H,I_H}}(t))^T$ is a vector (with $\sum_{h=1}^{H} \sum_{i=1}^{I_h} J_{h,i}$ dimensions) representing the retrofitting plan at the tth year. $x(t)$ is a vector of cumulative numbers of retrofitted facilities over t years. $f(\cdot)$ is the profit function of cost savings, and $g(\cdot)$ is the function of operational cost. Note that $CF(T) = f(x(T))$ here.

The profit function $f(x(t))$ is the financial benefit caused by energy savings, which in fact has a nonlinear form related with real-time pricing and individual profile of consumption. For simplicity, the profit function in this paper is expressed as a linear form

$$f(x(t)) = \sum_{h=1}^{H} \sum_{i=1}^{I_h} \sum_{j=1}^{J_{h,i}} r_{h,i}^{j} \cdot x_{h,i}^{j}(t) \cdot (1 + p)^{t-1}, \tag{8}$$

where $r_{h,i}^j$ is the average annual cost savings of the alternative intervention (h, i, j), and p is the increasing rate of electricity price.

The operational cost $g(u(t))$ includes labor cost, transportation cost, installation cost, and so on. In this paper, the operational cost is calculated in terms of each building and each facility as

$$g(u(t)) = \sum_{h=1}^{H} \sum_{i=1}^{I_h} \sum_{j=1}^{J_{h,i}} n_{h,i}^j \cdot u_{h,i}^j(t), \tag{9}$$

where $n_{h,i}^j$ is the operational cost for the retrofitted alternative intervention (h, i, j).

Similarly with Model B, energy savings ES and cash flow CF are actually influenced by facility decay in the large-scale BEER. The influences of decay should be considered in the large-scale BEER, like the decay model Eq. (4). Then the design of maintenance plan is necessary to overcome the deteriorated influences on energy savings and cash flow. As the scope here is focusing on the design of retrofitting plan, it is assumed that deteriorated or failed facilities are repaired or replaced instantly as

$$\sigma_i^j(t) = x_i^j(t) - \Delta(x_i^j(t)), t = 1, ..., T. \tag{10}$$

As the maintenance is instant, so the influences of decay can be neglected in the following parts for simplicity.

In the large-scale BEER model, total energy savings and net present value over the evaluation period T are expected to be maximized. These two objectives can be formulated as

$$\begin{cases} z_1 = \sum_{\tau=0}^{T} ES(\tau), \\ z_2 = \sum_{\tau=0}^{T} \frac{CF(\tau)}{(1+d)^\tau}, \end{cases} \tag{11}$$

where d is the discount rate that represents the rate of return could be earned in certain financial markets. z_1 denotes total energy savings, and z_2 denotes net present value.

The decision variable of the large-scale BEER model is constrained in the feasible space $\mathcal{U}$. The constraints include maximum limit of each type facility, energy saving target, and investment budget. The feasible space $\mathcal{U}$ can be expressed as

$$\mathcal{U} : \begin{cases} 0 \le u_{h,i}^j(t) \le q_{h,i}, t = 0, ..., T-1, \\ \sum_{\tau=0}^{T-1} \sum_{j=1}^{J_{h,i}} u_{h,i}^j(\tau) \le q_{h,i}, \\ \sum_{\tau=0}^{T} ES(\tau) \ge \alpha, \\ \sum_{\tau=0}^{t} CF(\tau) \ge -\sum_{\tau=0}^{t} \beta(\tau), t = 0...., T-1, \end{cases} \tag{12}$$

where $q_{h,i}$ is the total amount of the ith type existing facilities in the hth building ($h = 1, ...H$ and $i = 1, ..., I_h$); α is the energy saving target of project; $\beta(t)$ is the investment budget at the tth year. The energy saving target is typically to reduce 10% of original energy consumption. The investment budget is evenly allocated at the first t_0 years as

$$\beta(t) = \begin{cases} \beta', & t = 0, ..., t_0 - 1 \\ 0, & t \ge t_0, \end{cases} \tag{13}$$

where β' is the constant annual budget. In this study, it is assumed that $t_0 = 2$

The large-scale BEER is a multi-objective problem, in which Pareto optimal solutions are required to trade off different conflicting objectives. The multi-objective problem can be expressed as

$$\max z(u) = \max(z_1, z_2), \ u \in \mathcal{U}, \tag{14}$$

where $z = (z_1, z_2)$ represents a bi-objective function to be maximized. The multi-objective function has totally $T \sum_{h=1}^{H} \sum_{i=1}^{I_h} J_{h,i}$ dimensions, which can explain the reason of naming it the large-scale BEER problem.

4. An optimal control approach

The BEER model has been regarded as a constraint multi-objective optimization problem [17, 18, 19]. Optimization approaches, such as genetic algorithm [25], differential evolution [26] and neighborhood field optimization

[27, 28], have been employed to find a portion or the whole set of Pareto optima. The large-scale BEER model proposed here can also been solved by the optimization approaches, although the difficulty of global optimization increases exponentially as the dimension increases. To our best knowledge, the BEER problem is seldom studied in the control approach, however, the control approach could dynamically adjust the control input for overcoming system disturbances. This paper is a first attempt to study the large-scale BEER model in an approach of optimal control.

4.1. Control system

The large-scale BEER model is regarded as a control system in this paper. In the control system, retrofitting decision at each year is regarded as the system input $u(t)$; the cumulative number of items for each retrofitted facility is regarded as the system state $x(t)$; energy savings and cash flows are regarded as the system output $y(t) \triangleq (y_1, y_2)^T \triangleq (ES(t), CF(t))^T$. Denote $A = (a_{1,1}^1, ..., a_{1,1}^{J_{1,1}}, ..., a_{H,I_H}^{J_{H,I_H}})$, $B = (b_{1,1}^1, ..., b_{1,1}^{J_{1,1}}, ..., b_{H,I_H}^{J_{H,I_H}})$ and $R = (r_{1,1}^1, ..., r_{1,1}^{J_{1,1}}, ..., r_{H,I_H}^{J_{H,I_H}})$. When the operational cost is neglected, state-space equations can be deduced from Eq. (6) and (7) as

$$\begin{cases} x(t+1) = x(t) + u(t), \\ y(t) = C \cdot x(t) + D \cdot u(t), \end{cases} \tag{15}$$

where $x(0) = 0$; the output matrix C and the feed-forward matrix D can be formulated as

$$C = \begin{bmatrix} A \\ R \cdot (1+p)^{t-1} \end{bmatrix}, \tag{16}$$

$$D = \begin{bmatrix} 0 \\ -B \end{bmatrix}. \tag{17}$$

For the large-scale BEER, the two objectives energy savings and NPV are then transformed from Eq. (11) as

$$\begin{cases} z_1 = \sum_{t=0}^{T-1} y_1(t) + A \cdot x(T), \\ z_2 = \sum_{t=0}^{T-1} \frac{y_2(t)}{(1+d)^t} + \frac{(1+p)^{T-1}}{(1+d)^T} R \cdot x(T), \end{cases} \tag{18}$$

Note that the first component in each objective is the Lagrangian part, and the second component is the endpoint cost.

When the operational cost is considered, the state-space equation can be expressed as

$$\begin{cases} x(t+1) = x(t) + u(t), \\ y(t) = C \cdot x(t) + D \cdot u(t) + G(u(t)), \end{cases} \tag{19}$$

where $G(u(t)) = [0, -g(u(t))]^T$. In this paper, $g(u(t))$ has a linear form defined as Eq. (9).

4.2. Optimal control

Table 1: Detailed information of facilities and alternative interventions

Existing Facilities	q_1	q_2	Alternative interventions	$b_{h,i}^j$ (\$)	$a_{h,i}^j$ (kWh)	$r_{1,i}^j$ (\$)	$r_{2,i}^j$ (\$)
50 W downlight	145	165	35 W energy saving globe 1	14.19	102	5.2	5.2
			35 W energy saving globe 2	15.17	116	5.91	5.91
30 W recessed fitting	270	120	18 W retrofitting ECG 1	11.72	21	1.07	1.07
			18 W retrofitting ECG 2	11.11	20	1.02	1.02
			18 W retrofitting ECG 3	9.47	25	1.27	1.27
Old chiller	4	35	New chiller 1	147125	25392	13775.88	14050
			New chiller 2	139075	23539	12770.57	13000
Electric geyser 1	60	10	3 kW heat pump 1	1250	10989	794.11	850
			3 kW heat pump 2	1299.22	11166	807.24	865
			3 kW heat pump 3	1544.88	12074	872.88	950
Electric geyser 2	12	8	22 kW heat pump 1	13750	1006	1854.13	1910
			22 kW heat pump 2	12600	875	1612.69	1650
			22 kW heat pump 3	13768	1152	2123.22	2220
High-flow showerheads	360	50	Low-flow showerheads 1	11.25	278	18.61	18.61
			Low-flow showerheads 2	10.54	254	17	17

To maximize energy savings and NPV, the optimal control is utilized to design retrofitting strategies based on the proposed control system. In the optimal control, multiple objectives in large-scale BEER have to be combined into one objective function. According to Eq. (18) and (19), energy savings and NPV can be re-formulated as linear expressions

$$\begin{cases} z_1(u) = f_1 * u, \\ z_2(u) = f_2 * u, \end{cases} s.t.\ u \in \mathcal{U}, \tag{20}$$

where f_1 and f_2 are constant vectors that can be easily deduced from Eq. (18).

Usually, two objectives can be combined together for optimization. There are usually two ways of combination, i.e., weighted sum and weighted Tchebycheff methods [29]. Denote $\lambda = (\lambda_1, \lambda_2)$ that consists weighting values satisfying $\sum \lambda_k = 1$ and $0 \leq \lambda_k \leq 0$ $(k = 1, 2)$.

In the weighted sum method, two objectives are weighted by λ_1 and λ_2 respectively. The combined objective can be formulated as

$$\max \lambda_1 z_1 + \lambda_2 z_2, s.t.\ u \in \mathcal{U}, \tag{21}$$

where the control variable is bounded by $Q = (q_{1,1}, ..., q_{1,I_1}, ..., q_{H,I_H})^T$. Note the constraints $\mathcal{U}$ can be expressed as a linear form. The weighted sum method is effective to solve the problems with concave Pareto front, as the combined function has similar characteristics with each individual function. However, the weighted sum method shows its inability on the problems with non-concave Pareto front [30].

The weighted Tchebycheff method can overcome the weakness of the weighted sum method on non-concave problems. The weighted Tchebycheff metrics is defined as

$$||z^* - z||^\lambda = \max\{\lambda_1 |z_1^* - z_1|, \lambda_2 |z_2^* - z_2|\}, \tag{22}$$

where z_1^* is the maximum with respect to z_1; z_2^* is the maximum with respect to z_2. $z^* = (z_1^*, z_2^*)$ is called the ideal point in the Tchebycheff metrics. In the Tchebycheff method, this metrics will be minimized as

$$\min ||z^* - z||^\lambda, s.t.\ u \in \mathcal{U}, \tag{23}$$

in which different choices of weighting values can help to find the optimal solutions that are well-distributed on the Pareto front. As the Tchebycheff metrics is not differentiable, the difficult of optimization has increased in the weighted Tchebycheff method rather than the weighted sum method.

As energy savings and NPV have linear forms here, the Pareto front of the large-scale BEER problem is concave. According to empirical studies, it has been noticed that the weighted sum method and the weighted Tchebycheff method have delivered almost the same performance of accuracy and diversity. However, the weighted sum method requires much less computation time, so the weighted sum method is suggested in this application.

5. Experimental results

A building energy efficiency retrofit project, in which two buildings are involved, is investigated in this paper. The first building is a commercial building, and the second building is an office building. The electrical facilities mainly include 50W downlights, 30W recessed fitting lights, chillers, electric geysers, and showerheads. The auditing data has been given as q_1 and q_2 in Table 1. There are fewer chillers in the commercial building than those in the office building but more geysers in the commercial building. The retrofit budget in the 1st year is 0.1 million dollars, i.e. $\beta' = 100,000$. The same amount of budget is also invested in the 2nd year ($t_0 = 2$). It can be noticed that the studied project belongs to the large-scale BEER according to the scope definition. This project is associated with multi-year investment (time), multiple buildings, and multiple technologies as shown in the TBT framework. The effects of evaluation period are studied, so energy savings and NPV over 5 years and 10 years are given respectively. In this project, the target is to achieve $70,000,000$ kWh energy savings over 10 years and $35,000,000$ kWh over 5 years. The discount rate is 9%, and the increasing rate of electricity price is 7.1% in this study.

For each retrofitted facility, unit cost $b_{h,i}^j$ (\$), unit energy savings $a_{h,i}^j$ (kWh), and unit cost savings $r_{h,i}^j$ (\$) are listed in Table 1. For example, electronic control gear (ECG) technology is used to replace the recessed fitting. For chiller and geyser, the cost savings in the first building are different with those in the second building, as different locations and consuming patterns contribute different cost savings. The operational cost of the first building is assumed as $n^j_{1,i} = 0.03b^j_{1,i}$, and the operational cost of the second building is $n^j_{2,i} = 0.05b^j_{2,i}$.

In this section, three cases will be studied to verify the optimal control approach to the large-scale BEER model. In Case 1, energy savings over 5 years and 10 years are compared, i.e., $\lambda_1 = 1, \lambda_2 = 0$. In Case 2, NPV over 5 years and 10 years are compared, i.e., $\lambda_1 = 0, \lambda_2 = 1$. In Case 3, both two objectives over 5 years and 10 years are studied respectively. In Case 3, $\lambda_1 = 0.1, \lambda_2 = 0.9$ is used.

Table 2: Results of energy savings and NPV in case studies

	Case 1	Case 2	Case 3
ES (5 years)	$5.278 * 10^6$	$4.293 * 10^6$	$5.030 * 10^6$
NPV (5 years)	$-2.138 * 10^5$	$3.451 * 10^5$	$3.334 * 10^5$
ES (10 years)	$1.125 * 10^7$	$9.302 * 10^6$	$1.071 * 10^7$
NPV (10 years)	$-1.457 * 10^5$	$1.876 * 10^6$	$1.855 * 10^6$

In these 3 cases, energy savings and NPV achieved by the optimal approach have been listed in Table 2. In Case 1, the largest energy savings are achieved among 3 cases. Energy savings are $5.278 * 10^6$ kWh over 5 years and $1.125 * 10^7$ kWh over 10 years respectively. However, NPV in Case 1 is the smallest. NPV is \$ $-2.138 * 10^5$ over 5 years and \$ $-1.457 * 10^5$ over 10 years respectively. Here, negative NPV means that return is less than investment when only considering maximal energy savings. In Case 2, the largest NPV is achieved among 3 cases. NPV is \$ $3.451 * 10^5$ over 5 years and \$ $1.876 * 10^6$ over 10 years. However, energy savings in Case 2 are smallest. Therefore, it can be observed that energy savings and NPV are two conflicting targets. In Case 3, trade-off between energy savings and NPV can be achieved as both two objectives are optimized in the proposed approach. When comparing the results of 5 and 10 years, energy savings over 10 years are about 2 times as large as those over 5 years, but NPV over 10 years is much larger than that over 5 years.

Table 3: Optimal solution of the large-scale BEER project in Case 1 ($T = 5$)

	Building 1					Building 2				
Years Interventions	1	2	3	4	5	1	2	3	4	5
35 W energy saving globe 1	0	0	0	0	0	0	0	0	0	0
35 W energy saving globe 2	145	0	0	0	0	165	0	0	0	0
18 W ECG 1	0	0	0	0	0	0	0	0	0	0
18 W ECG 2	0	0	0	0	0	0	0	0	0	0
18 W ECG 3	270	0	0	0	0	120	0	0	0	0
New chiller 1	0	1	1	0	0	0	0	0	0	0
New chiller 2	0	0	0	1	1	0	0	0	0	0
3 kW heat pump 1	0	0	0	0	0	0	0	0	0	0
3 kW heat pump 2	0	0	0	0	0	0	0	0	0	0
3 kW heat pump 3	60	0	0	0	0	10	0	0	0	0
22 kW heat pump 1	0	0	0	0	0	0	0	0	0	0
22 kW heat pump 2	0	0	0	0	0	0	0	0	0	0
22 kW heat pump 3	1	0	0	0	0	0	0	0	0	0
Low-flow showerheads 1	360	0	0	0	0	50	0	0	0	0
Low-flow showerheads 2	0	0	0	0	0	0	0	0	0	0

For each case, the optimal solution over 5 years has been listed in Table 3, 4, and 5, respectively. In Table 3, for achieving the most energy savings, certain facilities, e.g., new chiller 2, are experienced retrofitting over the last few years in Case 1, which will introduce more cash outflow. That is the reason why NPV in Case 1 is the smallest. In details, 35 W energy saving globe 2, 18 W ECG 3, new chiller 1 and 2, and low-flow showerheads 1 are selected, as they have the best performance of energy saving in each type of facility. In Table 4, for achieving the largest NPV, all facilities are retrofitted at the first year. As no extra energy savings can be achieved, energy savings are the smallest in this case. The budget of the 2nd year is not invested as the evaluation period of 5 years is so short that the cost savings over this period cannot pay the investment. It can be noticed that the 1st building has higher priority of retrofitting than the 2nd building. The reason is that the operational cost of the 1st building is lower than the 2nd building. In Table 5, the optimal solution is a trade-off strategy of retrofitting.

The optimal solutions over 10 years have been plotted in Figure 2, 3, and 4, respectively. As the period is relatively long, the budget of the 2nd year can be spent for retrofitting. Energy and cost savings are expected to achieve more return of investment. In Case 1 (10 years), a number of facilities, e.g., chillers and geysers, will be retrofitted in

Table 4: Optimal solution of the large-scale BEER project in Case 2 ($T = 5$)

	Building 1					Building 2				
Years Interventions	1	2	3	4	5	1	2	3	4	5
35 W energy saving globe 1	0	0	0	0	0	0	0	0	0	0
35 W energy saving globe 2	145	0	0	0	0	0	0	0	0	0
18 W ECG 1	0	0	0	0	0	0	0	0	0	0
18 W ECG 2	0	0	0	0	0	0	0	0	0	0
18 W ECG 3	0	0	0	0	0	0	0	0	0	0
New chiller 1	0	1	0	0	0	0	0	0	0	0
New chiller 2	0	0	0	0	0	0	0	0	0	0
3 kW heat pump 1	0	0	0	0	0	0	0	0	0	0
3 kW heat pump 2	0	0	0	0	0	0	0	0	0	0
3 kW heat pump 3	60	0	0	0	0	0	0	0	0	0
22 kW heat pump 1	0	0	0	0	0	0	0	0	0	0
22 kW heat pump 2	0	0	0	0	0	0	0	0	0	0
22 kW heat pump 3	3	0	0	0	0	0	0	0	0	0
Low-flow showerheads 1	360	0	0	0	0	50	0	0	0	0
Low-flow showerheads 2	0	0	0	0	0	0	0	0	0	0

Table 5: Optimal solution of the large-scale BEER project in Case 3 ($T = 5$)

	Building 1					Building 2				
Years Interventions	1	2	3	4	5	1	2	3	4	5
35 W energy saving globe 1	0	0	0	0	0	0	0	0	0	0
35 W energy saving globe 2	145	0	0	0	0	165	0	0	0	0
18 W ECG 1	0	0	0	0	0	0	0	0	0	0
18 W ECG 2	0	0	0	0	0	0	0	0	0	0
18 W ECG 3	270	0	0	0	0	120	0	0	0	0
New chiller 1	0	1	0	0	0	0	0	0	0	0
New chiller 2	0	0	0	0	0	0	0	0	0	0
3 kW heat pump 1	0	0	0	0	0	0	0	0	0	0
3 kW heat pump 2	0	0	0	0	0	0	0	0	0	0
3 kW heat pump 3	60	0	0	0	0	10	0	0	0	0
22 kW heat pump 1	0	0	0	0	0	0	0	0	0	0
22 kW heat pump 2	0	0	0	0	0	0	0	0	0	0
22 kW heat pump 3	1	5	6	0	0	0	0	0	6	0
Low-flow showerheads 1	360	0	0	0	0	50	0	0	0	0
Low-flow showerheads 2	0	0	0	0	0	0	0	0	0	0

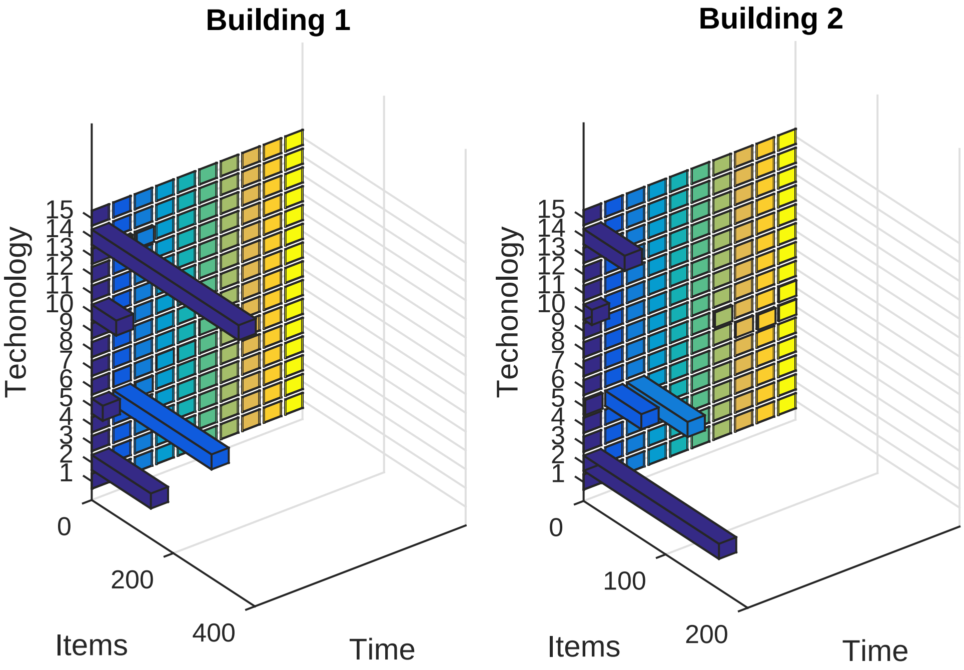

Figure 2: Optimal solutions in Case 1 (over 10 years). For each building, the vertical axis represents alternative interventions, and the horizontal axis represents years.

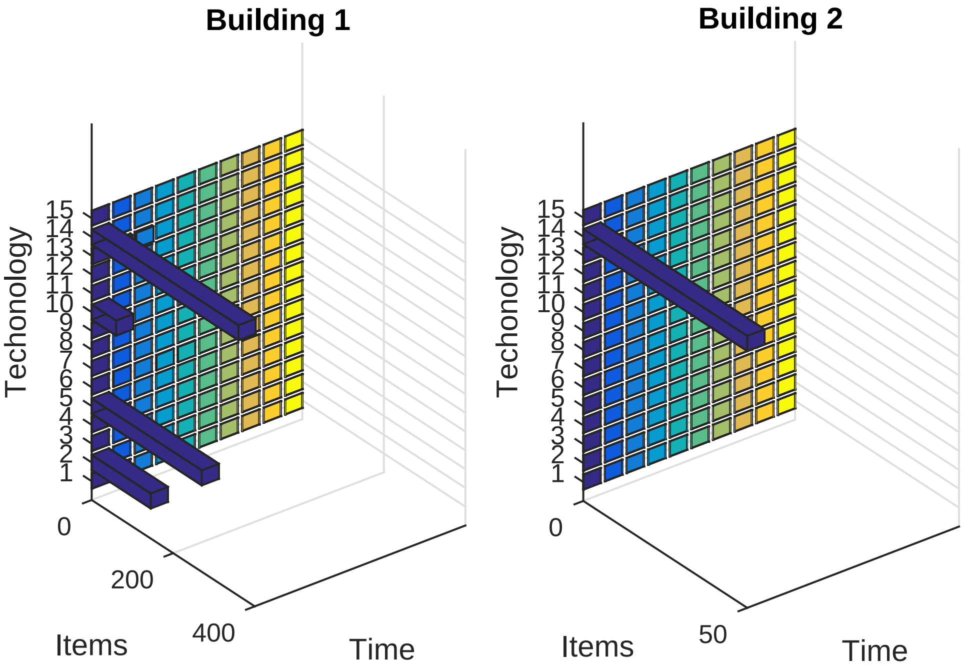

Figure 3: Optimal solutions in Case 2 (over 10 years). For each building, the vertical axis represents alternative interventions, and the horizontal axis represents years.

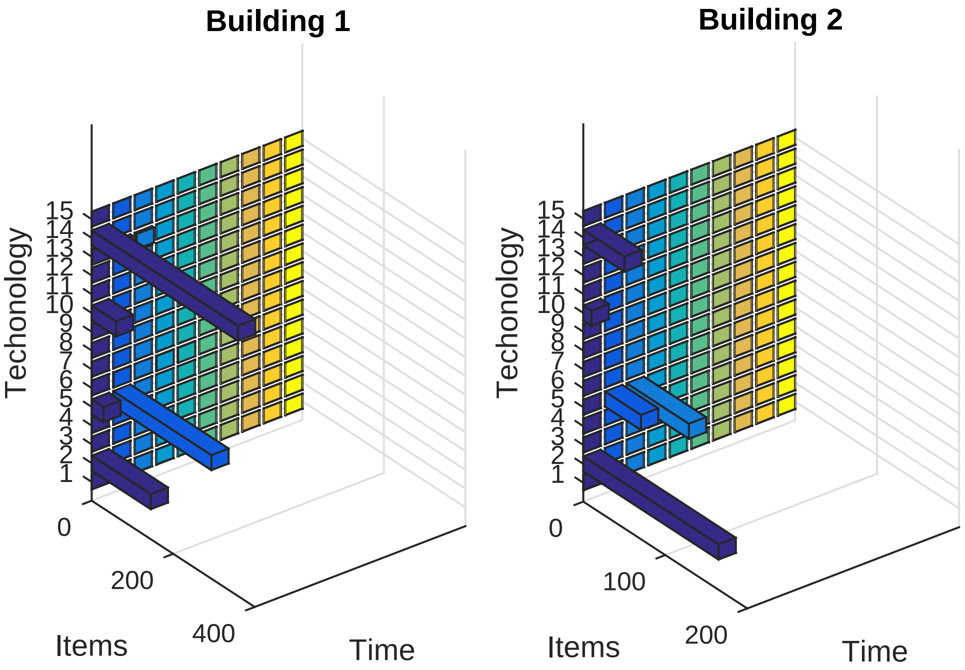

Figure 4: Optimal solutions in Case 3 (over 10 years). For each building, the vertical axis represents alternative interventions, and the horizontal axis represents years.

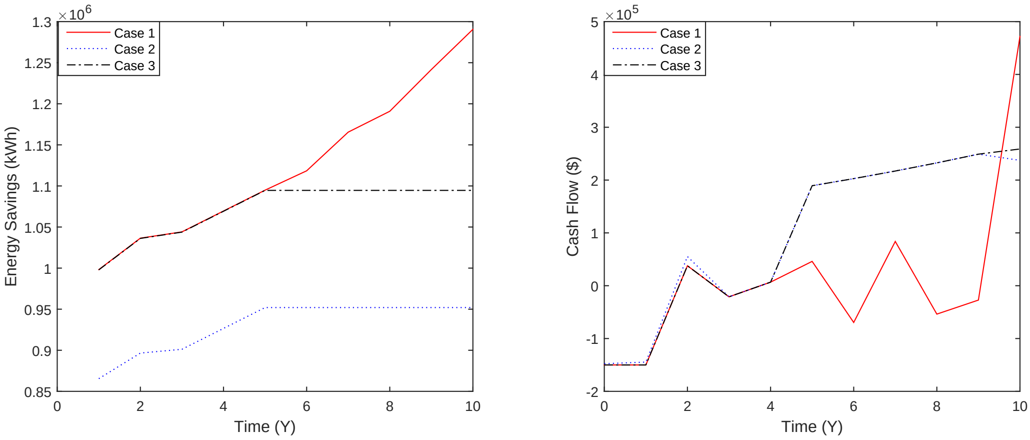

Figure 5: Profiles of energy savings and cash flows (over 10 years). Energy savings increase during the whole period, while the largest value is achieved in Case 1. The profiles of Cash flows are varying over time.

the two buildings as shown in Figure 2. In Case 2 (10 years) as shown in Figure 3, the 1st building is preferred to experience retrofitting as its operational cost is lower than that of the 2nd building. Similarly, the solution as shown in Figure 4 is a trade-off solution to balance the two conflicting objectives.

Over 10 years, the changes of energy savings and cash flows have been illustrated in Figure 5. In Case 1, energy savings are increasing at each year, as new retrofit is introduced at each year, which can be indicated by the cash flow profiles. The cash flows at the 6th, 8th and 9th years are negative, which means that cash is flowing out for the new retrofit. In Case 2, energy savings are keeping the same during the last 5 years, as no retrofit is introduced, which can be also indicated in the cash flow profiles. Energy savings in Case 3 are larger than those in Case 2, but the values are also keeping the same during the last 5 years. As observed in the cash-flow profiles, the reason of the largest NPV in Case 2 is that the least retrofit has been conducted at the start of the 2nd and 3rd years. To illustrate detailed dynamics of cash flows, the cash-in and cash-out flows over 10 years are plotted for Case 3, as shown in Figure 6. It can be noticed that in the first 4 years financial return caused by retrofitting is invested in the project to achieve more energy and cost savings. However, the financial return of latter years is not invested as it cannot be paid back by the limited energy savings.

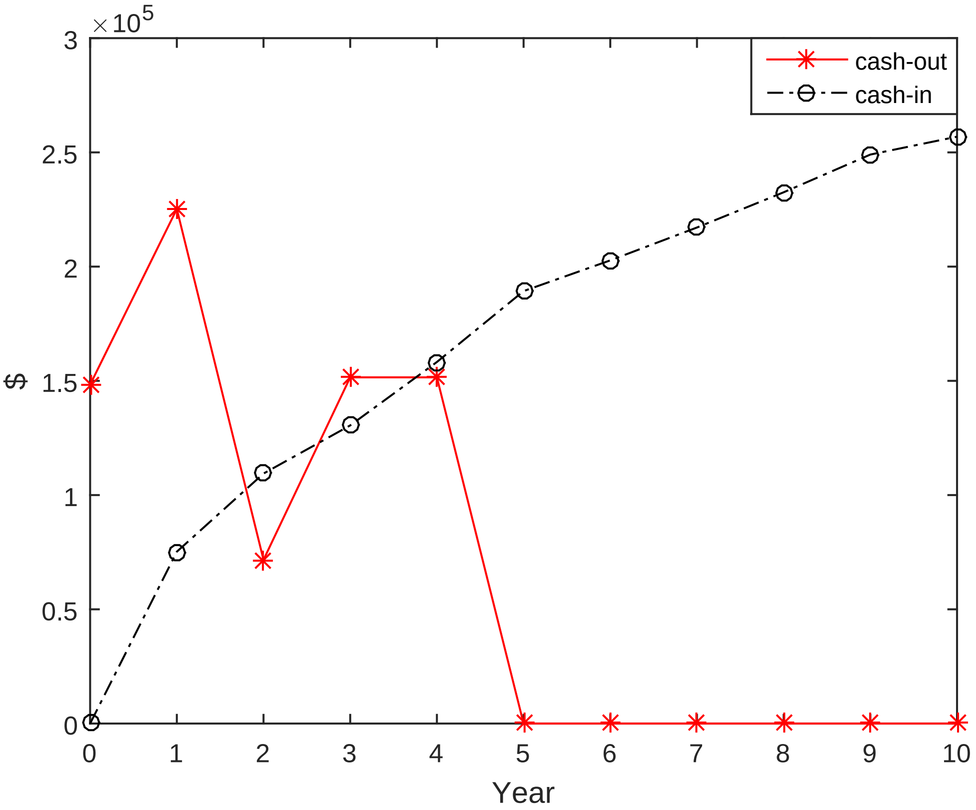

Figure 6: Profiles of cash-in and cash-out in Case 3 (over 10 years). Cash-in value is increasing due to cumulative energy savings. Cash-out value is not the same due to varying investment amount.

According to the above results, comparisons can be given between the large-scale BEER model and the existing models. In Model A, the same energy savings are achieved at each year; in Model B, energy savings possibly decrease over time due to facility decay; in the proposed model, energy savings could be increasing over time due to retrofit newly introduced. In Model A and B, cash flows are positive at each year after initial retrofit; in the proposed model, cash flows could be negative during the whole project period.

6. Conclusion

The large-scale BEER problem is newly defined as a TBT framework, in which retrofit could be conducted among multiple years, multiple buildings, and multiple types of facilities. This TBT framework can generalize most BEER studies in literatures, and also fit real situations faced in the high-level BEER projects, like government and regional projects. The design of retrofitting strategy has been studied in an optimal control approach for the large-scale BEER problem. The optimal strategy has to answer which building and which facility will experience retrofitting at each year.

Unlike optimization approaches in most studies of BEER, the retrofitting for each year is regarded as the control input, and the energy savings and NPV are regarded as the control outputs in the proposed control approach. In the control approach, energy and cost dynamics in the large-scale BEER are clearly unfolded. The TBT model and the optimal control approach are verified in real-world case studies.

Firstly, it is found that the building with lower operational cost has higher priority of retrofitting in the large-scale BEER problem. In the case studies, the first building is prior to the second building for retrofitting, as the operational cost of the first building is 60% of the second building. Secondly, retrofit is mostly conducted in the initial year when maximizing NPV. When maximizing energy savings, retrofit still proceeds at every year. Thirdly, the most economic technologies with respect to energy and cost savings have the highest priority to be selected in the large-scale BEER problems. These three observations have indicated that the system dynamics can be unfolded on 3 dimensions, i.e., building, time, and technology. The optimal solutions in the TBT framework can prove that the energy savings and NPV can be maximized in the proposed control approach.

Energy savings and NPV considered in this paper are two conflicting objectives. The largest energy savings and the largest NPV cannot be achieved at the same time. Optimal trade-off solutions can provide informative references to different stakeholders with different preferences. In this study, there is no prior knowledge of stakeholders' preferences in the optimal control approach. If certain preferences are known, they are possibly incorporated in the optimal control approach as well. For example, if certain facilities have to be retrofitted after other facilities, constraints about retrofitting sequence can be added; if one objective is more important than the others, weights can then be adjusted.

Optimal control is introduced as an example method in the proposed control approach to the large-scale BEER. Other robust closed-loop control methods can also be employed in the proposed approach, which could deliver robust performance of overcoming disturbances. However, these complicated situations as interesting topics of future work are not studied in this paper. Besides energy savings and NPV, other objectives, such as greenhouse gas emission, building value, and human comfort index, could also be optimized in the proposed optimal control approach. These objectives may be nonlinear and coupled with each other, then the large-scale BEER turns to be a complicated nonlinear control system that is left as part of future work.

References

[1] Wu Z, Tazvinga H, Xia X. Demand side management of photovoltaic-battery hybrid system. Applied Energy 2015;148:294 – 304.

[2] Ma Z, Cooper P, Daly D, Ledo L. Existing building retrofits: Methodology and state-of-the-art. Energy and Buildings 2012;55:889 – 902.

[3] Shao Y, Geyer P, Lang W. Integrating requirement analysis and multi-objective optimization for office building energy retrofit strategies. Energy and Buildings 2014;82:356 –68.

[4] Better buildigns challenge. U.S. DOE; 2014. Available from: https://www4.eere.energy.gov/challenge/home.

[5] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings; Official Journal of European Union, L 153, 18.6.2010 ed. European Commision; 2010.

[6] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC; Official Journal of European Union, L 315, 14.11.2012 ed. European Commision; 2012.

[7] Review of the Operational Efficiency of the Commercial Building Disclosure Program. Australian Government, Department of Industry; 2013. Available from: http://cbd.gov.au/review-of-the-operational-efficiency-of-the-cbd-program.

[8] Kaklauskas A, Zavadskas EK, Raslanas S. Multivariant design and multiple criteria analysis of building refurbishments. Energy and Buildings 2005;37(4):361 –72.

[9] Juan YK, Kim JH, Roper K, Castro-Lacouture D. GA-based decision support system for housing condition assessment and refurbishment strategies. Automation in Construction 2009;18(4):394 – 401.

[10] Ye X, Xia X, Zhang J. Optimal sampling plan for clean development mechanism energy efficiency lighting projects. Applied Energy 2013;112:1006 –15.

[11] Gustafsson SI. Sensitivity analysis of building energy retrofits. Applied Energy 1998;61(1):13 – 23.

[12] Ascione F, Bianco N, Stasio CD, Mauro GM, Vanoli GP. A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance. Energy and Buildings 2015;88:78 – 90.

[13] Diakaki C, Grigoroudis E, Kolokotsa D. Towards a multi-objective optimization approach for improving energy efficiency in buildings. Energy and Buildings 2008;40(9):1747 –54.

[14] Asadi E, Silva MGD, Antunes CH, Dias L. Multi-objective optimization for building retrofit strategies: A model and an application. Energy and Buildings 2012;44:81 –7.

[15] Karmellos M, Kiprakis A, Mavrotas G. A multi-objective approach for optimal prioritization of energy efficiency measures in buildings: Model, software and case studies. Applied Energy 2015;139:131 –50.

[16] Tan B, Yavuz Y, Otay EN, Çamlıbel E. Optimal selection of energy efficiency measures for energy sustainability of existing buildings. Computers & Operations Research 2015;In press.

[17] Malatji EM, Zhang J, Xia X. A multiple objective optimisation model for building energy efficiency investment decision. Energy and Buildings 2013;61:81 –7.

[18] Wang B, Xia X, Zhang J. A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings. Energy and Buildings 2014;77:227 –35.

[19] Wu Z, Xia X, Wang B. Improving building energy efficiency by multiobjective neighborhood field optimization. Energy and Buildings 2015;87:45 – 56.

[20] Wang B, Xia X. Optimal maintenance planning for building energy efficiency retrofitting from optimization and control system perspectives. Energy and Buildings 2015;96:299 – 308.

[21] Ye X, Xia X, Zhang L, Zhu B. Optimal maintenance planning for sustainable energy efficiency lighting retrofit projects by a control system approach. Control Engineering Practice 2015;37:1 – 10.

[22] Krarti M. Evaluation of large scale building energy efficiency retrofit program in kuwait. Renewable and Sustainable Energy Reviews 2015;50:1069 –80.

[23] Heo Y, Augenbroe G, Graziano D, Muehleisen RT, Guzowski L. Scalable methodology for large scale building energy improvement: Relevance of calibration in model-based retrofit analysis. Building and Environment 2015;87:342 –50.

[24] Carstens H, Xia X, Ye X. Improvements to longitudinal clean development mechanism sampling designs for lighting retrofit projects. Applied Energy 2014;126:256 –65.

[25] Vose MD. The simple genetic algorithm: foundations and theory; vol. 12. MIT press; 1999.

[26] Storn R, Price K. Differential evolution–a simple and efficient heuristic for global optimization over continuous spaces. Journal of global optimization 1997;11(4):341–59.

[27] Wu Z, Chow T. A local multiobjective optimization algorithm using neighborhood field. Structural and Multidisciplinary Optimization 2012;46(6):853–70.

[28] Wu Z, Chow T. Neighborhood field for cooperative optimization. Soft Computing 2013;17(5):819–34.

[29] Steuer R, Choo EU. An interactive weighted tchebycheff procedure for multiple objective programming. Mathematical Programming 1983;26(3):326–44.

[30] Zhang Q, Li H. MOEA/D:A multiobjective evolutionary algorithm based on decomposition. IEEE Transactions on Evolutionary Computation 2007;11(6):712–31.