Applied Energy 228 (2018) 2140–2152

Contents lists available at ScienceDirect

Applied Energy

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

Building retrofit optimization models using notch test data considering energy performance certificate compliance

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HIGHLIGHTS

- Two simplified optimization models for whole-building retrofit planning are proposed.
- The models reduce the complexity of systematic building retrofit planning problems.
- The models eliminate a costly detailed bottom-up energy audit process.
- The models consider green building policy based on EPC and the tax incentive.
- The models can be of great help for retrofit plans for a building portfolio.

ARTICLE INFO

Keywords:
Whole-building retrofit
Energy performance certificate
Grouping
Notch test data
Green building

ABSTRACT

Determining a systematic whole-building retrofit plan for envelope components and indoor appliances to achieve targets such as cost savings and policy compliance is a challenging task. To be specific, the systematic whole-building retrofit problem, when solved by an optimization approach, is highly complicated. It is sometimes even impossible to find a solution with given computation resources and algorithms. In addition, a costly comprehensive bottom-up audit is required to establish the parameters of the problem. This study presents two models to reduce the complexity of the systematic whole-building retrofit optimization problem. Firstly, the proposed models use the grouping concept to optimize the retrofit of subsystems in a building instead of individual components/appliances, which reduces the dimension of the problem effectively. Secondly, the models use so-called 'notch test' data, which are sampled and verified savings of an intervention, to eliminate the need for bottom-up energy audits. This further simplifies the retrofit optimization problem and reduces the retrofit cost. The models are based on our previous work and aim at energy savings maximization and payback period minimization, considering the green building policy and tax incentive initiatives. A case study shows that about 2530 MWh energy savings and an A rating from the energy performance certificate standard can be obtained with a payback period of 59 months, which verifies the feasibility and effectiveness of the models proposed.

1. Introduction

Globally, the building sector accounts for around 30–40% of total energy consumption [1]. Statistics show that this number is even higher in the European Union [2]. This high energy usage by the building sector is mainly attributed to existing buildings [3] and still keep increasing, because of the low construction rate of new buildings and the fact that new buildings are more energy-efficient owing to tighter energy regulations introduced [4]. In view of this, retrofitting existing buildings with energy-efficient technologies to bring down their energy intensities is an effective and common approach to facilitate the transition to a green building sector, which is proved by the investigation on building retrofit potential in [5], the studies on office building retrofit in [6] and sustainable building retrofit decisions in [7]. For instance, energy-efficient lightings are useful to reduce the energy usage of artificial lighting [8], good window technologies promote better energy-saving ventilation [9], and heating, ventilation and air conditioning (HVAC) help to reduce the energy consumed by cooling [10], heating and ventilation [11] and to promote a healthy indoor environment [12].

Many policies around the world are implemented to promote a green building sector that utilizes energy efficiently, such as the

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https://doi.org/10.1016/j.apenergy.2018.07.043
Received 23 April 2018; Received in revised form 6 July 2018; Accepted 12 July 2018

Leadership in Energy and Environmental Design (LEED) certification program [13], Building for Environment and Economic Sustainability [14], the Green Star rating system [15], the Canadian green building tool [16], the Italian regulation [17], etc. The South African government has also released a green building rating policy based on the energy intensity of buildings, namely the energy performance certificate (EPC) for buildings [18]. The purpose is to compel building owners or managers to reduce the energy demand of their buildings by implementing energy-efficient interventions. The green building policy is proposed to be applied to public buildings first and to all kinds of buildings at a later stage. Seven energy intensity ratings, ranging from grade A (most energy-efficient) to grade G (most energy-inefficient), are available from the EPC system. The effectiveness of the EPC standard depends on two aspects. One is the effective implementation and monitoring of the EPC. South African government has published a policy that prohibits the use of buildings not complying with the required EPC level to promote implementation and monitoring of buildings' energy usage. The other is the accuracy of energy performance evaluation [19]. The evaluation is addressed by a scientific measurement and verification (M&V) approach [20]. The uncertainty of the energy performance evaluation depends on many factors, such as measurement uncertainty, modeling uncertainty etc. [21]. In this study, real-world 'notch test' data are used to improve accuracy and hence uncertainty of the EPC certification process. Given the aforementioned background, it is essential to develop methods to retrofit buildings in a cost-effective manner, not only to achieve energy and cost savings, but also to adhere to the green building policy introduced.

In the literature, studies on the economic perspective of green building rating and building energy performance contracting projects were reported recently. For instance, Qian and Guo [22] built a revenue-sharing bargaining model for energy performance contracting projects. Castro-Lacouture et al. [23] developed an optimal design model for buildings for the purpose of maximizing the credits under the LEED rating system and [24] proposed an optimization model aiming at maximizing the economic benefits, energy and water savings as well as LEED points. However, no study that can be used to support decision makers technically, considering building retrofit investment for the purpose of EPC compliance, can be found in the literature. In particular, the EPC standard requires the energy intensity of the whole building to be reduced, which calls for a whole-building retrofit approach, considering both indoor appliances and the envelope components and interactions between them.

Existing studies relevant to building retrofit from the literature can be categorized into two general types, namely studies on the building envelope system and indoor appliances. With respect to the envelope system, Asadi et al. [25] proposed a multi-objective optimization method to help decision makers to determine intervention measures for the purpose of minimizing building energy consumption in a cost-effective manner. Güçyeter and Günaydın [26] evaluated and optimally determined retrofit strategies for a building envelope system by a calibrated simulation method based on energy audit and monitoring. Edeisy and Cecere [27] investigated envelope retrofit as a tool to increase comfort levels and decrease cooling loads in hot, arid climates. Fan and Xia [28] developed an optimization method for building envelope retrofit planning, considering a roof-top photovoltaic (PV) system, for energy efficiency improvement. Regarding indoor appliances, Kang and Liu [29] proposed a multi-objective optimization model on a heat exchanger network retrofit with a heat pump for simultaneously minimizing the retrofit cost and maximizing the CO_2 emission reduction. Cartens et al. [30] developed a model for reducing the cost and energy consumption in clean development mechanism lighting retrofit projects. Wang and Xia [31] introduced a control system framework to tackle the retrofit planning problems for indoor appliances to reduce energy intensity.

Very few studies on determining systematic retrofit plans for a whole building have been reported. To this end, our previous work [32] presented an approach to identifying systematic whole-building retrofit plans for existing buildings considering both the envelope components and the indoor appliances with the purpose of maximizing energy savings and green building policy compliance. However, determining such a systematic whole-building retrofit plan with the approach proposed in [32] is quite complex. Firstly, the large numbers of items to be retrofitted and those of the available alternatives for retrofit result in a high-dimensional optimization problem. This makes the problem difficult to solve when coupled with the mixed integer decision variables involved. Secondly, the conflicting objectives, such as maximizing energy savings and minimizing the payback period, and the nonlinear characteristics of the optimization problem make it even more challenging to find the optimal solution. This situation is further worsened especially when the building to be retrofitted has a large number of floors (or similar functional areas) that cause a linear increase in the dimension of the decision variables. The same problem is experienced by managers investigating retrofit options for a building portfolio consisting of multiple buildings. Thirdly, there are a large number of parameters to be obtained for the systematic whole-building retrofit problems. This usually requires a detailed energy audit of the buildings to be retrofitted, which is an expensive bottom-up modeling exercise.

Therefore, this study puts forward two methods to reduce the complexity of the systematic whole-building retrofit optimization problem and to eliminate the need for a bottom-up energy audit. These methods are based on the concept of grouping and measured energy savings data from sample retrofits.

The grouping method is used to categorize items to be retrofitted into several homogeneous groups [33]. Items are considered to be homogeneous and assigned to a group if they have a similar energy performance, inherent properties, working environment and operating schedules. This is motivated by the fact that energy-consuming systems in a building can be classified into lighting systems, HVAC systems, envelope systems, etc., and each of these systems usually consists of items that have the same characteristics. On a larger scale, each of these systems in a big building or building group can be treated as a virtual 'item' because of their similar functionality and characteristics.

Given the large number of items in a building for possible retrofit, it is very difficult to evaluate all the possibilities of retrofitting each energy-consuming item. In contrast, the dimension of the decision variables can be reduced significantly [34] by making use of the grouping method, because the solution will only determine whether a group of items should be retrofitted or not and which retrofit option should be chosen for the group instead of determine this for each single item. This is also in good agreement with the expectations of the decision makers because they will usually retrofit the whole group of similar units to facilitate easy maintenance and retrofit labor cost, etc.

In this study, items with the same energy performance and cost implications are grouped together. In addition, it must be pointed out that this study considers buildings with a large number of similarly designed and operated floors or functional areas. All homogeneous items within the boundary of a floor or a functional area comprise a subset of the overall homogeneous group of items for the whole building and will be termed an 'item' of the overall group in the rest of this study. For example, all light bulbs in a building belong to the same group and lambs on one floor constitute a virtual 'item' of the lighting group. After dividing the retrofitted items of the building into several homogeneous groups, the overall retrofit performance of the building, such as energy savings and cost, can be evaluated by investigating the performance of retrofitting an individual member and the number of retrofitted members of each homogeneous group.

The whole-building retrofit problem is further simplified by making use of measured energy savings achieved by retrofitting items of a homogeneous group. This is supported by the large number of energy conservation initiatives implemented across the world. In South Africa, for example, many building retrofit projects have been implemented and the energy savings of these projects have been quantified by the M&

V approach [35]. The verified energy savings of retrofitting different systems in a general building, including an envelope system, lighting system, HVAC system, etc., are the so-called 'notch test' data, which can be used to simplify the optimization problem. To be specific, knowing the potential energy savings and corresponding cost of retrofitting each subsystem on one floor of the building with a certain alternative, one can determine the best combination of subsystems and alternatives that could be used for the whole building retrofit so that the given objectives of the optimization problem are achieved.

In summary, the two models proposed categorize the items of target buildings into several homogeneous groups. Knowing the available energy savings of retrofitting an item of each group from existing retrofits, the models can work out systematic optimal retrofit plans for buildings by optimizing the numbers of virtual 'items' of each group and the retrofit options for them. The difference between the two methods is that the first one limits the retrofit options for the 'items' in the same group to be the same, while the second one does not.

The main contributions of this paper are listed as follows:

- Two simplified optimization models are proposed to reduce the complexity of systematic whole-building retrofit planning problems.
- The simplification is based on grouping method and 'notch test' data, which decreases the dimension of the optimal building retrofit planning problem and eliminates the need for a costly detailed bottom-up energy audit process.
- The models developed can help decision makers to determine energy-efficient and cost-effective whole-building retrofit plans in a computationally less expensive manner.
- The models take into account the South African green building policy based on EPC and the tax incentive initiative program for energy saving projects such that all possible benefits of the building retrofit project are explored and all constraints are considered in the planning phase.
- The proposed models can be of great help to decision makers to investigate retrofit plans for a building portfolio consisting of multiple buildings.
- The simplified models developed can be applied to similar building retrofit optimization projects that aim at reducing complexity and eliminating a comprehensive energy audit.

It is also noted that although the models presented are developed with particularly the South African environment in mind, they are applicable to general green building retrofit projects where energy intensity reduction and cost-effectiveness are the main concerns.

Because the systematic whole-building retrofit problem is a nonlinear mixed integer programming problem, modern optimization methods must be employed to solve this problem. Given the wide variety of modern optimization approaches, the literature has been investigated and it was found that the genetic algorithm is proved to be a better method to solve this type of problem [36]. In [37], a real coded genetic algorithm is proposed for solving integer and mixed integer optimization problems. Juan et al. [38] also chose a genetic algorithm to solve office building renovation problems considering energy performance improvement. The genetic algorithm is a method for solving optimization problems based on natural selection and evolutionary biology. It reflects the process of natural selection, which is that the fittest individuals are chosen for reproduction, aiming at producing offspring of the next generation. Genetic algorithms are capable of solving a variety of optimization problems, which cannot be dealt with by standard optimization algorithms, such as discontinuous, non-differentiable, mixed integer or highly nonlinear issues [39].

The remaining part of this paper is organized as follows. Two models for the simplification of the systematic whole-building retrofit problems are presented in Section 2. Section 3 provides a case study and results analysis. Conclusions are drawn in Section 4.

2. Optimization models

In this section, the aforesaid two simplified optimization models for systematic whole-building retrofit planning considering both the envelope components and the indoor appliances are developed. The purposes of the two optimization models are the same as those given in [32], which is to maximize the energy savings, minimize the payback period of building retrofit projects and make sure the buildings can obtain a good energy rating from the EPC standard for green building policy compliance.

The two simplified optimization models are built under the premise given below:

- The building to be retrofitted has the same structure for each floor.
- The intention is to retrofit energy consumption subsystems, such as lighting envelope, etc. on each floor of the building rather than single items. For instance, all the luminaries rather than part of them on one floor will be replaced with new ones if the lighting system on that floor is to be retrofitted.
- Proper maintenance for the items retrofitted during the project period is implemented so that the energy savings of the retrofit project are persistent.

In this study, the energy consumption in a building is divided into lighting systems, envelope systems (window and wall), HVAC systems (chiller and heat pump) and the roof system for upgrading with energy-efficient interventions. In addition, a PV power supply system is considered to be installed to reduce the building's energy demand from the grid [40] and ensure better life quality for occupants [41] owing to the rich solar resource in South Africa. Because the structure of each floor of the building is the same, the energy performance, inherent properties, working environment and operating schedules of the lighting subsystems and envelope subsystems of each floor are considered to be the same. According to grouping, all the lights within the building can be grouped into a homogeneous group, with all the lights installed on each floor as a virtual item of this group. The same is done for the envelope systems. The roof only has one item because for each building, there is only one roof structure. The HVAC systems in this study are of a centralized type. With this grouping and notch test data for retrofitting an item in these homogeneous groups, one can determine the impact of retrofitting a homogeneous group of items (subsystems) on the whole building.

Assume that there are I alternatives of windows and J alternatives of wall insulation materials for retrofitting the envelope systems, K alternatives of roof insulation materials for retrofitting the roof, C alternatives of chillers and H alternatives of heat pumps for retrofitting the HVAC systems, and P alternatives of solar panels for the PV system installation. For the lighting systems, assume that there are m types of existing lighting to be retrofitted and there are L_m alternatives for retrofitting the m-th type. It follows that there are $(I+1)(J+1)$ retrofit options for the envelope systems, $(C+1)(H+1)$ retrofit options for the HVAC systems, $(L_1+1)(L_2+1), \ldots, (L_m+1)$ retrofit options for the lighting systems, $(K+1)$ retrofit options for the roof, and $(P+1)$ options for the PV system installation. Let e, v and u denote that the e-th option for the envelope systems, the v-th option for the HVAC systems and u-th option for the lighting systems are chosen to replace the corresponding existing components, respectively. The values of e, v and u take integer values defined in (1)–(3).

$$e \in \{1, 2, \ldots, (I+1)(J+1)\}, \tag{1}$$

$$v \in \{1, 2, \ldots, (C+1)(H+1)\}, \tag{2}$$

$$u \in \{1, 2, \ldots, (L_1+1)(L_2+1)\ldots(L_m+1)\}. \tag{3}$$

There is strong coupling between the envelope and the HVAC systems in their energy performance because the thermal performance of the envelope systems affects the load of the HVAC systems. As a consequence, these two subsystems are considered together to achieve energy savings. In this case, there are $(I+1)(J+1)(C+1)(H+1)$ retrofit options for the combined system. Let r, defined in (4), denote the r-th option for the combined system, i.e., the e-th option for the envelope systems and the v-th option for the HVAC systems, are chosen for the retrofit. The selection of the envelope, HVAC and lighting systems can thus be represented by the values of r and u.

$$r \in \{1, 2, \ldots, (I+1)(J+1)(C+1)(H+1)\}. \tag{4}$$

With the above information, the detailed formulations of the two models considering the retrofit of a building with F floors over the project period of T years are given in the following subsections.

2.1. Optimization model I

Optimization model I solves the whole building retrofit problem by assuming that the optimal retrofit options for each floor of the building are the same to simplify the problem further. For instance, if the e-th option for the envelope system and the u-th option for the lighting system are chosen by the optimization model, each floor of the building will use these options for its retrofit. Because the structure and functions of all the floors are the same, the optimization determines the optimal retrofit options r, u and the number of floors to retrofit their subsystems with these optimally selected options. In addition, the optimization will, at the same time, optimally determine the option of the PV system, the number of PV panels to be installed, and the optimal solution for the roof retrofit.

2.1.1. Decision variables of optimization model I

The decision variable of the systematic building retrofit optimization problem following optimization model I is given by:

$$X_1 = [r, u, N_{env,f}, N_{lig,f}, k, p, N_{pv}],$$

where $N_{env,f}$ denotes the number of floors to retrofit the envelope systems, $N_{lig,f}$ denotes the number of floors to retrofit the lighting systems, N_{pv} is the number of solar panels to be installed; $k \in \{1, 2, \ldots, (K+1)\}$ and $p \in \{1, 2, \ldots, (P+1)\}$ mean that the k-th roof alternative is chosen and the p-th solar panel alternative is installed, respectively.

2.1.2. Objectives of optimization model I

The objectives of the building retrofit project include energy savings and the payback period, which are important indicators to evaluate the profitability of an investment [42].

The energy savings of the building retrofit project in year t, $ES_1(t)$, can be calculated by

$$\begin{aligned} ES_1(t) = {} & N_{lig,f} ES_{lig}(u) + ES_{rof}(k, v) + ES_{pv}(p) N_{pv} + N_{env,f} ES_{mix}(r) \\ & + (F - N_{env,f}) ES_{mix}(r - e + 1), \end{aligned} \tag{5}$$

where $ES_{mix}(r)$ is the energy savings on one floor after retrofitting the floor's envelope and the building's HVAC system with the r-th option measured in Wh, $ES_{lig}(u)$ is the energy savings of retrofitting one floor's lighting system with the u-th option measured in Wh, $ES_{rof}(k, v)$ is the energy savings of retrofitting the roof of the building with its k-th option when the HVAC systems are retrofitted with the v-th option, measured in Wh and $ES_{pv}(p)$ is the energy production of one solar panel of the p-th option measured in Wh. The second term in (5) represents the energy savings achieved by retrofitting the centralized HVAC systems on the floors whose envelope systems are not retrofitted.

Taking into account the discount rate and the tax incentive program, the payback period of the building retrofit project T_{p1} is calculated by the following equations:

$$T_{p1} = t + \frac{|\overline{C_f}(t)|}{C_f(t+1)}, \tag{6}$$

$$C_f(t) = \frac{p(t) ES_1(t) + R(t)}{(1+d)^t} - C_{r1}, \tag{7}$$

$$R(t) = \begin{cases} (E_{pre} - E_{post}) \zeta_a \zeta_t, & t = 1, \\ 0, & \text{otherwise.} \end{cases} \tag{8}$$

In Eqs. (6)–(8), t is an integer and is the last period with a negative cumulative discounted cash flow, $\overline{C_f}(t)$ is the absolute value of cumulative cash flow at the end of period t measured in Dollar ($), $C_f(t+1)$ is the discounted cash flow in the period after t measured in $, $p(t)$ is the electricity price in year t measured in $/Wh, d is the discount rate, $R(t)$ is the tax incentive measured in $, E_{pre} and E_{post} are the total energy consumption of the building before and after the retrofit, respectively, measured in Wh/year, ζ_a is the allowance rate and ζ_t is the tax rate for general businesses in South Africa. C_{r1} is the retrofit cost making use of optimization model I measured in $ and can be calculated by

$$\begin{aligned} C_{r1} = {} & N_{env,f}(C_{mix}(r) - C_{hva}(v)) + N_{lig,f} C_{lig}(u) \\ & + C_{rof}(k) + C_{pv}(p) N_{pv} + C_{hva}(v), \end{aligned} \tag{9}$$

where $C_{mix}(r)$ is the cost of retrofitting one floor's envelope systems and the building's HVAC systems with the r-th option measured in $, $C_{lig}(u)$ is the cost of retrofitting one floor's lighting system with the u-th option measured in $, $C_{hva}(v)$ is the cost of retrofitting the HVAC systems of the building with the v-th option measured in $, $C_{rof}(k)$ is the cost of retrofitting the roof of the building with the k-th option measured in $, $C_{pv}(p)$ is the cost of one solar panel of the p-th option measured in $.

In the literature, the weighted sum method was widely used to solve multiple objective optimization problems [43]. For instance, Kim and de Weck [44] investigated adaptive weighted sum method for multi-objective issues and [45] employed this approach for energy-efficient investment decision problems. Therefore, the weighted sum method is chosen to solve the optimization problem formulated, resulting the following objective function:

$$J = -w_1 \sum_{t=1}^{T} ES_1(t) + w_2 T_{p1}. \tag{10}$$

2.1.3. Constraints of optimization model I

The constrains of the optimal retrofit problem include three parts, which are the EPC limit, budget limit and physical limits.

The EPC rating system assigns a rating to a building based on its energy intensity compared to a reference value set by the South African national standard [46]. The requirements of getting a certain rating from the EPC are detailed in Table 1. The item E_r is the reference energy intensity, which depends on the occupancy class and location of the building.

Based on the requirements of different ratings in Table 1, the EPC limit used to ensure that the building obtains the desired rating from the EPC standard for the purpose of green building policy compliance, can be described by the following general formulas [18]:

$$E_p < \delta E_r, \tag{11}$$

Table 1
Energy performance scale.

Grade	Requirement
A	Energy intensity $< 0.3E_r$
B	$0.3E_r \leqslant$ Energy intensity $< 0.6E_r$
C	$0.6E_r \leqslant$ Energy intensity $< 0.9E_r$
D	$0.9E_r \leqslant$ Energy intensity $< 1.1E_r$
E	$1.1E_r \leqslant$ Energy intensity $< 1.4E_r$
F	$1.4E_r \leqslant$ Energy intensity $< 1.7E_r$
G	Energy intensity $\geqslant 1.7E_r$

$$E_p = \frac{E_{post}}{A_g}, \tag{12}$$

where E_p denotes the energy intensity of the building measured in kWh/m^2, A_g is the gross area of the building measured in m^2, δ is a coefficient, taking the values from Table 1. For instance, $\delta = 1.1$ means that at least a D rating must be obtained for the building.

The budget limit for the retrofit can be described with the following formula:

$$C_{r1} \leqslant \beta, \tag{13}$$

where β is the retrofit budget measured in \$.

The physical limits include the available roof area for the PV system installation, given as follows:

$$A_{pv}(p)N_{pv} \leqslant A_{eff}, \tag{14}$$

where $A_{pv}(p)$ is the area of one solar panel of the p-th option measured in m^2 and A_{eff} is the usable area of the roof for PV system installation measured in m^2.

All the decision variables must satisfy the following integer constraints:

$$\begin{aligned}
&N_{env,f} \in \{0, 1, \ldots, F\},\\
&N_{lig,f} \in \{0, 1, \ldots, F\},\\
&r \in \{1, 2, \ldots, (I+1)(J+1)(C+1)(H+1)\},\\
&u \in \{1, 2, \ldots, (L_1+1)(L_2+1)\ldots(L_m+1)\},\\
&k \in \{1, 2, \ldots, (K+1)\},\\
&p \in \{1, 2, \ldots, (P+1)\}.
\end{aligned} \tag{15}$$

2.2. Optimization model II

Based on optimization model I and on [32], which allows each item to flexibly choose desired alternatives for retrofit, one can naturally think of a second simplified method, which might find better solutions compared with model I. The differences between the two methods are detailed as follows.

- Method II makes it possible for each floor to have different retrofit options, *i.e.* the same subsystem on all floors can be retrofitted with different options.
- It might be capable of making more complete use of investment and finding better retrofit plans owing to the flexibility of retrofit options.
- It might make a relatively small compromise in the complexity reduction of the retrofit optimization problem.

Since each floor of the building can determine whether its subsystems are to be retrofitted or not, the aim of second optimization model is to prepare an optimal retrofit plan for the whole-building retrofit with a given budget by determining the retrofit states and retrofit options for the energy-consuming subsystems of each floor and the roof and HVAC systems of the building, the installation option for the PV system and the number of solar panels to be installed.

2.2.1. Decision variables of optimization model II

The decision variable of the building retrofit optimization following model II is described by:

$$X_2 = [v, e_1, \ldots, e_f, \ldots, e_F, u_1, \ldots, u_f, \ldots, u_F, k, p, N_{pv}],$$

where e_f and u_f denote that the e_f-th option for the envelope system and the u_f-th option for the lighting systems are chosen for retrofitting the f-th floor.

2.2.2. Objectives of optimization model II

The same objectives, including energy savings and the payback period, are considered.

The energy savings of the building retrofit project in year t, $ES_2(t)$, can be calculated by the following equation:

$$ES_2(t) = \sum_{f=1}^{F} (ES_{mix}(v, e_f) + ES_{lig}(u_f)) + ES_{rof}(k, v) + ES_{pv}(p)N_{pv}, \tag{16}$$

where $ES_{mix}(v, e_f)$ is the energy savings of the f-th floor after its envelope systems retrofitted with the e_f-th option and the building's HVAC systems have been retrofitted with the v-th option, measured in Wh, $ES_{lig}(u_f)$ is the energy savings of the f-th floor after its lighting systems have been retrofitted with the u_f-th option, measured in Wh.

The resulting retrofit cost of the second model, C_{r2}, can be calculated by

$$C_{r2} = \sum_{f=1}^{F} [C_{mix}(v, e_f) - C_{hva}(v) + C_{lig}(u_f)] + C_{rof}(k) + C_{pv}(p)N_{pv} + C_{hva}(v), \tag{17}$$

where $C_{mix}(v, e_f)$ is the cost of retrofitting the building's HVAC systems with the v-th option and the envelope systems of the f-th floor with the e_f-th option, measured in \$, $C_{lig}(u_f)$ is the cost of retrofitting the lighting systems of the f-th floor with its u_f-th option, measured in \$.

The payback period of the building retrofit project T_{p2} can be calculated following Eqs. (6)–(8).

Taking advantage of the Eqs (16) and (17), the objective function of this model is given by

$$J = -w_1 \sum_{t=1}^{T} ES_2(t) + w_2 T_{p2}. \tag{18}$$

2.2.3. Constraints of optimization model II

The budget limit can be described with the following in equation:

$$C_{r2} \leqslant \beta. \tag{19}$$

The EPC rating limit can be described with formulas (11) and (12). The PV installation area limit is described by formula (14). The limits on the design variables are:

$$\begin{aligned}
&k \in \{1, 2, \ldots, (K+1)\},\\
&p \in \{1, 2, \ldots, (P+1)\},\\
&v \in \{1, 2, \ldots, (C+1)(H+1)\},\\
&e_f \in \{1, 2, \ldots, (I+1)(J+1)\},\\
&\forall f \in \{1, 2, \ldots, F\},\\
&u_f \in \{1, 2, \ldots, (L_1+1)(L_2+1)\ldots(L_m+1)\},\\
&\forall f \in \{1, 2, \ldots, F\}.
\end{aligned} \tag{20}$$

3. Case study

3.1. Case information

In this section, an existing office building is used as a case study to verify the viability of the two optimization models. The building studied comprises six floors with the same structure, shown in Fig. 1. The area of each floor is $266\,\text{m}^2$. Before the retrofit, the EPC rating of the building under study is grade E. Therefore, this building has to improve its energy efficiency to achieve a D rating at least to comply with the green building policy. The information on the alternatives for retrofitting the envelope, lighting, HVAC and roof systems and installing the PV system are detailed in Tables 2–8, (The data in this paper are obtained from manufactures product datasheets, data obtained from hundreds of M&V projects, published technical reports, and the South African national standards, etc.). For example, Table 8 gives the information of the alternative lighting technologies used to retrofit the corresponding existing lighting technologies. The economic parameters

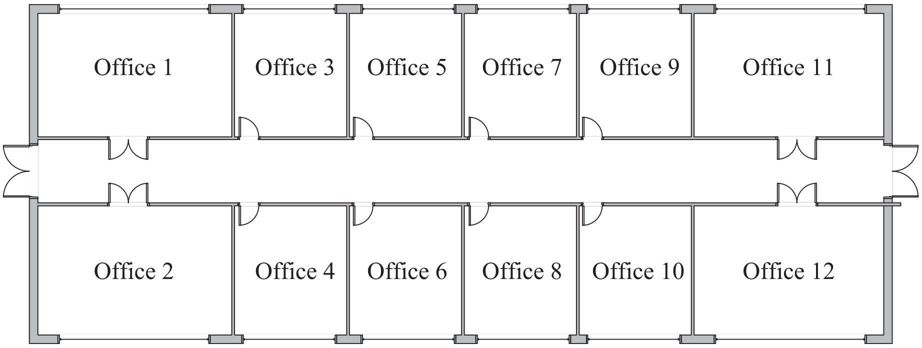

Fig. 1. Floor design of the office building under study.

Table 2
Window alternatives.

i	Alternatives	U_i (W/m °C)	$C_{win,i}$ (\$/m^2)
1	Double glazing, tinted uncoated air-filled metallic frame	0.49	50.00
2	Double glazing, tinted coated air-filled metallic frame	0.38	80.00
3	Double glazing, low-e window, air-filled metallic frame	0.32	97.00

Table 3
Wall insulation material alternatives.

j	Alternatives	d_j (m)	λ_j (W/m °C)	$C_{wal,j}$ (\$/m^2)
1	Glass wool	0.05	0.038	16.32
2	EPS	0.08	0.033	21.10
3	Cork	0.30	0.040	69.38

Table 4
Roof insulation material alternatives.

k	Alternatives	d_k (m)	λ_k (W/m °C)	$C_{rof,k}$ (\$/m^2)
1	SPF	0.020	0.042	8.23
2	EPS	0.060	0.033	10.49
3	Stone wool	0.105	0.037	44.84

Table 5
Chiller alternatives.

c	Alternatives	SEER	$C_{chi,c}$ (\$)
1	Trane chiller type 1	17.0	8580
2	Trane chiller type 2	15.0	7590

Table 6
Heat pump alternatives.

h	Alternatives	HSPF	$C_{pum,h}$(\$)
1	Trane heat pump type 1	9.5	7920
2	Trane heat pump type 2	8.6	7425

Table 7
Solar panel alternatives.

p	Alternatives	$C_{pv,p}$ (\$)	η_l (%)	$A_{pv,p}$ (m^2)
1	YL190P-23B	592.62	14.7	1.297
2	CS6X-300P	870.33	15.6	1.919
3	SW 275 MONO	1042.50	16.4	1.593

Table 8
Lighting technology alternatives.

l_m	Existing lighting	N_{l_m}	Alternatives	C_{lig_m,l_m} (\$)
l_1	2-lamp 4′ T8 fixture 70 W	80		
			2-lamp 4′ T5 14 W	19.0
			2-lamp 4′ T5 18 W	20.5
			2-lamp 4′ T5 36 W	10.0
l_2	PAR 38–65 W	48		
			CFL lamp 7 W	35.4
			CFL lamp 14 W	37.1
			CFL lamp 20 W	27.6
l_3	Incandescent 100 W	32		
			LED bulb 12 W	79.5
			LED bulb 17 W	53.0
			LED bulb 20 W	42.4

involved in the optimization models include the discount rate and the increased rate of the electricity price, which are determined as 6% and 12.69%, respectively, according to South Africa's economic statistics and the largest utility, Eskom, in South Africa.

3.2. Data collection

According to Section 2, there are 144 retrofit options for the combined envelope and HVAC systems, 64 retrofit options for the lighting systems, 36 retrofit options for the roof considering the HVAC systems and four options for the PV system installation. The notch test data on retrofitting the envelope, lighting, HVAC and roof of the building and installing a roof-top PV system on the building obtained following the M&V method are detailed in Tables 11–14, which are presented in the appendix. For instance, the resulting energy savings and the corresponding cost of retrofitting the envelope of one floor and the HVAC systems of the building with different combined options are detailed in Table 11. The numbers in the row corresponding to $r = 103$ of Table 11 detail the 103-rd retrofit option for this floor's envelope and the building's HVAC systems. Specifically, the data mean that the heat pump in the HVAC is not retrofitted, the chiller is retrofitted with its second alternative listed in Table 6, the windows are replaced with the first alternative listed in Table 2 and the walls are fitted with the second insulation alternative given in Table 3. Retrofitting one floor with this option results in 5349 kWh energy savings and costs \$14335.

In this study, the building retrofit optimization problem is solved by a genetic algorithm. To investigate the impact of investments on the optimal retrofit plans, the results of applying the optimal plans obtained by the two optimization models proposed in Section 2 with different budgets are presented in the following sections. Optimization results with different budgets set to \$10,000, \$25,000, \$45,000 and \$200,000 are analyzed.

The two optimization models are both solved using the weighted sum method to give decision makers a convenient way to obtain a desired retrofit plan according to their preferences on different objectives

Table 9
Results of applying optimization model I with different budgets.

Description	Budget1	Budget2	Budget3	Budget4
β (\$)	10000	25000	45000	200000
C_{r1} (\$)	9263	24586	44683	196490
r	1	1	49	85
$N_{env,f}$	0	0	0	2
u	52	24	23	22
$N_{lig,f}$	4	6	6	6
(v, k)	1	1	13	21
p	2	2	2	3
N_{pv}	2	0	16	163
T_{p1} (month)	22	22	27	59
ES_1 (kWh)	561286	1501978	1873954	2530403
E_p	0.927	0.617	0.494	0.278
RSD of T_{p1}	2.67%	2.65%	0.83%	3.55%
RSD of ES_1	3.40%	4.46%	0.14%	0.16%
RSD of E_p	0.68%	3.29%	0.18%	0.48%

by tuning the weighting factors. In order to verify this, the effectiveness of tuning the weighting factors is studied. The impact of the tax incentive program on the optimal retrofit plan is also analyzed.

3.3. Results analysis

3.3.1. Results analysis of optimization model I

To verify the feasibility of the first optimization model for systematic whole-building retrofit planning, the optimal solutions with different budgets based on the method are presented in Table 9.

In Table 9, the detailed optimal retrofit plans for the building with different investments are indicated by the contents from the fourth (starting with C_{r1} (\$)) to the tenth row. r represents the retrofit options for the envelope systems of each floor and the HVAC systems of the building. u represents the retrofit option for the lighting systems of each floor. $N_{env,f}$ and $N_{lig,f}$ indicate the numbers of floors to retrofit their envelope systems and lighting systems, respectively. (v, k) represents the retrofit options listed in Table 13 for the roof system of the building considering the HVAC systems. p and N_{pv} indicate the option and number of installed PV panels shown in Table 14. For instance, the number '85' for r means that the 85-th option for the envelope systems and the HVAC systems is chosen for retrofit with a budget of \$200000. The number '49' for r means the 49-th option is chosen, which indicates that the envelope systems of the building are not retrofitted. Only the HVAC systems of the building are retrofitted with the budget of \$45000. '2' for $N_{env,f}$ means that the envelope systems of two floors of the building are retrofitted. The number '23' for u and '6' for $N_{lig,f}$ in the fourth column represent that the lighting systems of all six floors are retrofitted with the 23-rd option with a budget of \$45000. The numbers '13' and '21' for (v, k) both represent that the roof system of the building is not retrofitted, referring to Table 13. The number '2' for p and '16' for N_{pv} in the fourth column mean that the second option in Table 14 is chosen for setting up the PV system and 16 of the selected solar panels are installed.

When investigating the optimal retrofitting solutions in Table 9, it is observed that the proposed methods do not simply choose the cheapest options or the most energy-efficient ones. For instance, the optimal retrofit plan with a budget of \$10000 selects the 52-th option from Table 8 for retrofitting the lighting systems, which is not the cheapest or the most energy-efficient option among the alternatives in Table 8.

The items ES_1 and T_{p1} represent the resulting energy savings and payback period of the building retrofit project making use of optimization model I. It can be seen that the energy savings and payback period keep increasing with growing budgets. The reason for this phenomenon is that more investments allow more systems to be retrofitted, thereafter resulting in more energy savings and longer payback periods. One also finds that the growth rate of the payback period increases with growing budgets. This is because more and more systems with long payback are retrofitted when the budget increases. For instance, only the lighting systems are retrofitted with the budget of \$25,000. However, 16 solar panels are installed with the budget of \$45,000. When the budget increases to \$200,000, more solar panels are installed and the envelope systems of some floors are also retrofitted.

An interesting phenomenon is that the payback period with a budget of \$10,000 is the same as that with a budget of \$25,000. This can be explained by the cost-effectiveness of retrofitting different subsystems with different options. Retrofitting the lighting systems is the most cost-effective method to save energy, followed by retrofitting the HVAC systems. Installing a PV system and retrofitting the envelope systems require long payback periods. With the budget of \$25000, all the investment is used to retrofit the lighting systems, while part of the investment is used to install a PV system with the budget of \$10,000. In addition, the 24-th option chosen for retrofitting the lighting systems with the budget of \$25,000 is more energy-efficient compared with the 52-nd one and results in a relatively shorter payback period. This explains the nearly identical payback periods of the two investments.

When investigating the optimal retrofit actions with different budgets, one finds that the lighting systems of four floors of the building are retrofitted with the 52-nd option and two solar panels of its second option in Table 14 are installed with the budget of \$10,000. However, the lighting systems of all the floors are retrofitted while no PV panel is installed when the budget increases to \$25,000. When the investment grows to \$45,000, all the lighting systems of the building are retrofitted with a more energy-efficient option and the HVAC systems are also retrofitted. In addition, 16 solar panels of the second option are installed. With an even higher budget, \$200,000, available, the envelope systems of some floors are retrofitted, better options are selected for retrofitting other subsystems, and more solar panels are installed. In view of the above, a conclusion can be drawn that the investment gives priority to the subsystems of the building in the order of the lighting, HVAC, PV, envelope and the roof. This is because retrofitting the lighting systems is the most cost-effective choice to save energy, followed by the HVAC systems. Retrofitting the envelope and roof systems and installing a PV power supply system take a long time to pay back the cost in spite of their large energy saving potentials.

One of the purposes of this study is to improve the energy efficiency of the building to achieve a good EPC rating for green building policy compliance. In Table 9, E_p represents the energy performance of the building after applying the optimal retrofit plan obtained from optimization model I. Compared with the reference value in Table 1, one finds that the four optimal retrofit plans obtained with budgets of \$10000, \$25000, \$45000 and \$200000 can help the building to get a D, C, B and A rating from EPC, respectively.

Because the problem is solved by a genetic algorithm, which is essentially a metaheuristic method, the variance of the solutions must be investigated. In Table 9, the RSD values [47] of T_{p1}, ES_1 and E_p represent the relative standard deviations of the payback period, energy savings of the building retrofit project and the energy performance of the building achieved by the retrofit calculated from 20 runs of the genetic algorithm, respectively. It can be seen that the RSD values of these items are less than 5%, which means the results obtained with optimization model I are stable.

To demonstrate the effectiveness of weighting parameter tuning, the optimization problem is solved with two more sets of weighting factors and the results obtained are presented in Fig. 2. For convenience of comparison, other factors that affect the retrofit project remain the same. In particular, the budget is kept at \$10000 and the tax incentive program is taken into account during these optimization processes. In Fig. 2, it can be seen that the energy savings increase and the payback period decreases when their corresponding weighting factors grow. For instance, the percentage of energy savings of the building retrofit project increases from 1.9% to 17.2% when the value of its corresponding

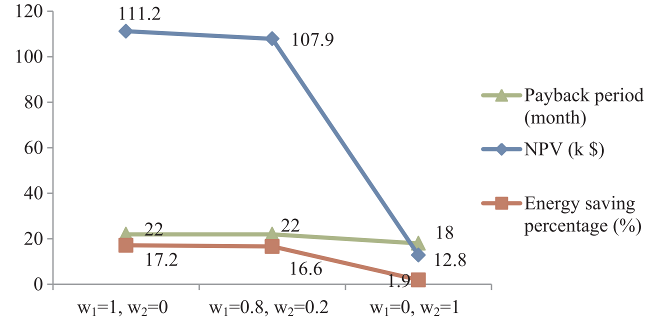

Fig. 2. Optimal results obtained by optimization model I with different weighting factors.

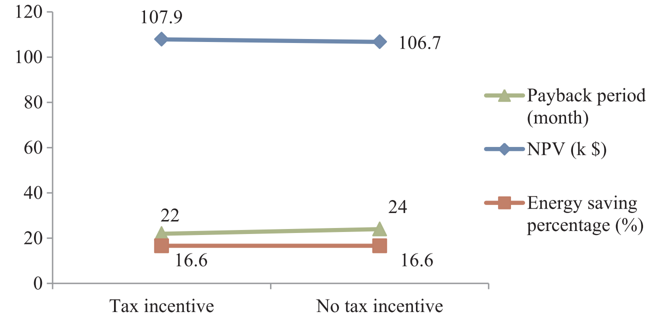

Fig. 3. Impact of tax incentive on the optimal results obtained by optimization model II with $w_1 = 0.8$, $w_2 = 0.2$, β = "$"10, 000.

Table 10

Results of applying optimization model II with different budgets.

Description	Budget1	Budget2	Budget3	Budget4
β ($)	10000	25000	45000	200000
C_{r2} ($)	9860	24925	44936	199593
r_1	1	1	49	69
r_2	1	1	49	65
r_3	1	1	49	69
r_4	1	1	49	65
r_5	1	1	49	65
r_6	1	1	49	69
u_1	56	23	23	23
u_2	1	24	23	22
u_3	1	24	24	22
u_4	64	24	23	22
u_5	1	24	23	22
u_6	64	24	23	22
(v, k)	1	1	13	17
p	4	2	2	3
N_{pv}	0	0	17	163
T_{p2} (month)	22	22	27	60
ES_2 (kWh)	594086	1504742	1875121	2531403
E_p	0.916	0.616	0.494	0.277
RSD of T_{p2}	2.00%	1.95%	3.55%	2.69%
RSD of ES_2	1.74%	3.47%	3.64%	0.64%
RSD of E_p	0.36%	2.54%	3.62%	1.79%

weighting factor w_1 changes from zero to one. The payback period of the project decreases from 22 months to 18 months when the value of its corresponding weighting factor w_2 increases from zero to one. In view of the results in Fig. 2, it can be concluded that optimization model I gives decision makers the flexibility of obtaining the desired result according to their preferences on energy savings or payback period.

To investigate the impact of the tax incentive program on the building retrofit project, the optimization problem is solved by optimization model I without considering the tax incentive and the results are presented in Fig. 3. In Fig. 3, one finds that considering the tax incentive program in the optimization process results in a slightly shorter payback period and higher net present value. This verifies that the tax incentive program is capable of further shortening the payback period of the building retrofit project.

3.3.2. Results analysis of optimization model II

The optimal solutions obtained by optimization model II with different budgets are provided in Table 10, in which r_1, r_2, r_3, r_4, r_5 and r_6 represent the retrofit options from Table 11 for the envelope systems of the six floors and the HVAC system of the building. u_1, u_2, u_3, u_4, u_5 and u_6 represent the retrofit options from Table 12 for the lighting systems of the six floors.

The same trend reported in Section 3.3.1 is observed in Table 10. For example, retrofit plans obtained by optimization model II with budgets of $10000, $25000, $45000 and $200000 can help the building under study to get a D, C, B and A rating from the EPC, respectively. The RSD values of T_{p2}, ES_2 and E_p are less than 5%, which verifies the stability of optimization model II in finding optimal retrofit plans for buildings.

3.4. Comparison of the two models

Following the two simplified methods, the number of decision variables of compiling a systematic retrofit plan for a whole building is reduced from hundreds (even more) to a small value compared with that of [32]. Both methods reduce the complexity of solving whole-building retrofit problems and eliminate the need for a comprehensive energy audit.

From a theoretical point of view, model I and model II differ in resolution of the grouping of items to be retrofitted. Model I essentially groups all items on a floor as a virtual item, whereas model II treats subsystems such as lighting systems and HVAC systems, as individual items. More detailed grouping in model II contributes to better utilization of the available investment, as discussed earlier. It must be pointed out at this stage that the differences in the grouping method adopted by the two models will be studied further in future research on how to design an optimal model and a corresponding grouping method that results in an acceptable precision and confidence level of the model predicted energy savings while effectively reducing the complexity of the retrofit optimization problem. This is particularly relevant because it was shown by researchers from the same research group that similar grouping methods will not affect the final performance of the retrofit planning problem significantly [33]. In other words, theoretical comparison of the two simplification models presented in this study is still an open research question and the design of a method to select an optimization model considering its precision and complexity at the same time is being actively investigated currently.

For practical applications, conclusions on how to select the two developed models for a specific application are drawn as detailed below, according to the findings of the case study.

For small-scale building retrofit problems, model II is more accurate and performs better than model I. This is because model II allows the retrofit options for all the subsystems in the building to be different. Its flexibility promotes better utilization of the available investment. This can be verified by dividing the C_r by β in Tables 9 and 10. The results show that the utilization rate of the budget is between 98.6% and 99.8% with model II, while the same rate ranges from 92.6% to 99.3% with model I. In fact, the results in Tables 9 and 10 indicate that model II produces better results than model I in terms of absolute energy savings. For instance, 33 MWh extra energy is saved by model II with a budget of $10000 compared to model I.

With respect to building retrofit problems with a large number of floors involved, model I is simpler and more effective than model II. This is because the dimension of the optimization problem is much less for model I compared with that of model II, especially when a large number of floors are involved. There are only five decision variables in optimization model I, whereas the number of decision variables in optimization model II is $2F + 4$, which depends on the number of floors in the building. When the number of floors increases, the number of decision variables of model I will remain unchanged, while that of model II will increase rapidly. Therefore, solving retrofit problems for buildings with a large number of floors using model II is relatively more difficult compared to using model I. In addition, the solution obtained with method II might sometimes be very poor when a large number of decision variables are involved because of the inefficiency of existing algorithms to solve integer programming problems.

In practical applications, one first need to obtain information of the target building to be retrofitted, such as its existing energy-consuming systems, and conduct a notch test of retrofitting a certain item by a particular alternative (this can also be taken from similar projects). Then, the developed models in this paper can be directly used with the obtained parameters to solve for the optimal retrofit plan. The idea of the simplified models has already been used in hundreds of M&V energy saving projects undertaken by the Center of M&V at the University of Pretoria, such as the energy efficiency lighting projects [8]. In addition, the proposed models are useful to help decision makers obtain optimal retrofit plans for a building portfolio consisting of multiple buildings, which is a common challenge in practice.

4. Conclusion

In this study, two simplified optimization models are proposed to reduce the complexity of systematic whole-building retrofit planning problems considering both the envelope components and indoor appliances. The two retrofit models aim at saving energy and achieving desired green building ratings by implementing energy-efficient interventions in the most cost-effective way. The simplification is done by using a grouping method and measured and verified energy savings of sample retrofits. The simplification not only reduces the complexity of the retrofit optimization problem in terms of technical difficulty and computational load of solving the problem, but also helps to obviate the need for an expensive detailed energy audit to support the retrofit planning. The two models proposed are tested with a case study and both are shown to be effective in achieving the objectives of this study. The simplified optimization methods are suitable for reducing complexity and eliminating a detailed energy audit of all building retrofit optimization problems.

Appendix A

Tables 11–14.

Table 11
Notch test data of retrofitting a floor's envelope and the building's HVAC system.

$r(v, e)$	Chiller	Heat pump	Window	Wall	$ES^{mix}(r)$ (kWh)	$C^{mix}(r)$ ($)
1	0	0	0	0	0	0
2	0	0	0	1	67	2544
3	0	0	0	2	75	3289
4	0	0	0	3	83	10815
5	0	0	1	0	2393	3456
6	0	0	1	1	2460	6000
7	0	0	1	2	2468	6745
8	0	0	1	3	2476	14271
9	0	0	2	0	2018	5530
10	0	0	2	1	2085	8074
11	0	0	2	2	2093	8819
12	0	0	2	3	2101	16345
13	0	0	3	0	2144	6705
14	0	0	3	1	2211	9249
15	0	0	3	2	2219	9994
16	0	0	3	3	2227	17520
17	0	1	0	0	290	7920
18	0	1	0	1	320	10464
19	0	1	0	2	323	11209
20	0	1	0	3	327	18735
21	0	1	1	0	2656	11376
22	0	1	1	1	2685	13920
23	0	1	1	2	2689	14665
24	0	1	1	3	2693	22191
25	0	1	2	0	2280	13450
26	0	1	2	1	2309	15994
27	0	1	2	2	2313	16739
28	0	1	2	3	2317	24265
29	0	1	3	0	2406	14625
30	0	1	3	1	2435	17169
31	0	1	3	2	2439	17914
32	0	1	3	3	2443	25440
33	0	2	0	0	279	7425
34	0	2	0	1	310	9969
35	0	2	0	2	314	10714
36	0	2	0	3	318	18240
37	0	2	1	0	2646	10881
38	0	2	1	1	2677	13425
39	0	2	1	2	2681	14170
40	0	2	1	3	2684	21696
41	0	2	2	0	2270	12955

(*continued on next page*)

Table 11 (*continued*)

$r(v, e)$	Chiller	Heat pump	Window	Wall	$ES^{mix}(r)$ (kWh)	$C^{mix}(r)$ ($)
42	0	2	2	1	2301	15499
43	0	2	2	2	2305	16244
44	0	2	2	3	2308	23770
45	0	2	3	0	2396	14130
46	0	2	3	1	2427	16674
47	0	2	3	2	2431	17419
48	0	2	3	3	2434	24945
49	1	0	0	0	4870	8580
50	1	0	0	1	4924	11124
51	1	0	0	2	4930	11869
52	1	0	0	3	4937	19395
53	1	0	1	0	5391	12036
54	1	0	1	1	5445	14580
55	1	0	1	2	5452	15325
56	1	0	1	3	5458	22851
57	1	0	2	0	5315	14110
58	1	0	2	1	5369	16654
59	1	0	2	2	5376	17399
60	1	0	2	3	5382	24925
61	1	0	3	0	5342	15285
62	1	0	3	1	5396	17829
63	1	0	3	2	5402	18574
64	1	0	3	3	5409	26100
65	1	1	0	0	5160	16500
66	1	1	0	1	5177	19044
67	1	1	0	2	5179	19789
68	1	1	0	3	5181	27315
69	1	1	1	0	5655	19956
70	1	1	1	1	5671	22500
71	1	1	1	2	5673	23245
72	1	1	1	3	5675	30771
73	1	1	2	0	5577	22030
74	1	1	2	1	5594	24574
75	1	1	2	2	5596	25319
76	1	1	2	3	5598	32845
77	1	1	3	0	5604	23205
78	1	1	3	1	5620	25749
79	1	1	3	2	5622	26494
80	1	1	3	3	5624	34020
81	1	2	0	0	5149	16005
82	1	2	0	1	5167	18549
83	1	2	0	2	5169	19294
84	1	2	0	3	5171	26820
85	1	2	1	0	5645	19461
86	1	2	1	1	5663	22005
87	1	2	1	2	5665	22750
88	1	2	1	3	5667	30276
89	1	2	2	0	5568	21535
90	1	2	2	1	5586	24079
91	1	2	2	2	5588	24824
92	1	2	2	3	5590	32350
93	1	2	3	0	5594	22710
94	1	2	3	1	5612	25254
95	1	2	3	2	5614	25999
96	1	2	3	3	5616	33525
97	2	0	0	0	4701	7590
98	2	0	0	1	4756	10134
99	2	0	0	2	4762	10879
100	2	0	0	3	4769	18405
101	2	0	1	0	5288	11046
102	2	0	1	1	5342	13590
103	2	0	1	2	5349	14335
104	2	0	1	3	5355	21861
105	2	0	2	0	5201	13120
106	2	0	2	1	5256	15664
107	2	0	2	2	5262	16409
108	2	0	2	3	5269	23935
109	2	0	3	0	5231	14295
110	2	0	3	1	5286	16839
111	2	0	3	2	5292	17584
112	2	0	3	3	5299	25110
113	2	1	0	0	4992	15510
114	2	1	0	1	5009	18054
115	2	1	0	2	5011	18799
116	2	1	0	3	5013	26325

(*continued on next page*)

Table 11 (*continued*)

$r(v,e)$	Chiller	Heat pump	Window	Wall	$ES^{mix}(r)$ (kWh)	$C^{mix}(r)$ ($)
117	2	1	1	0	5551	18966
118	2	1	1	1	5568	21510
119	2	1	1	2	5570	22255
120	2	1	1	3	5572	29781
121	2	1	2	0	5463	21040
122	2	1	2	1	5481	23584
123	2	1	2	2	5483	24329
124	2	1	2	3	5485	31855
125	2	1	3	0	5493	22215
126	2	1	3	1	5510	24759
127	2	1	3	2	5512	25504
128	2	1	3	3	5514	33030
129	2	2	0	0	4981	15015
130	2	2	0	1	4999	17559
131	2	2	0	2	5001	18304
132	2	2	0	3	5004	25830
133	2	2	1	0	5541	18471
134	2	2	1	1	5560	21015
135	2	2	1	2	5562	21760
136	2	2	1	3	5564	29286
137	2	2	2	0	5454	20545
138	2	2	2	1	5472	23089
139	2	2	2	2	5474	23834
140	2	2	2	3	5477	31360
141	2	2	3	0	5483	21720
142	2	2	3	1	5502	24264
143	2	2	3	2	5504	25009
144	2	2	3	3	5506	32535

Table 12
Notch test data of retrofitting the lighting system of one floor.

u	Light 1	Light 2	Light 3	$ES^{lig}(u)$ (kWh)	$C^{lig}(u)$ ($)
1	0	0	0	0	0
2	0	0	1	8110	2544
3	0	0	2	7649	1696
4	0	0	3	7373	1357
5	0	1	0	7016	1487
6	0	1	1	15126	4031
7	0	1	2	14665	3183
8	0	1	3	14388	2844
9	0	2	0	6169	1558
10	0	2	1	14279	4102
11	0	2	2	13818	3254
12	0	2	3	13542	2915
13	0	3	0	5443	1158
14	0	3	1	13553	3702
15	0	3	2	13092	2854
16	0	3	3	12816	2514
17	1	0	0	10644	1254
18	1	0	1	18755	3798
19	1	0	2	18294	2950
20	1	0	3	18017	2611
21	1	1	0	17660	2741
22	1	1	1	25770	5285
23	1	1	2	25309	4437
24	1	1	3	25033	4098
25	1	2	0	16813	2812
26	1	2	1	24924	5356
27	1	2	2	24463	4508
28	1	2	3	24186	4169
29	1	3	0	16088	2412
30	1	3	1	24198	4956
31	1	3	2	23737	4108
32	1	3	3	23460	3768
33	2	0	0	9884	1354
34	2	0	1	17994	3898
35	2	0	2	17533	3050
36	2	0	3	17257	2711

(*continued on next page*)

Table 12 (*continued*)

u	Light 1	Light 2	Light 3	$ES^{lig}(u)$ (kWh)	$C^{lig}(u)$ ($)
37	2	1	0	16900	2841
38	2	1	1	25010	5385
39	2	1	2	24549	4537
40	2	1	3	24273	4198
41	2	2	0	16053	2913
42	2	2	1	24163	5457
43	2	2	2	23702	4609
44	2	2	3	23426	4269
45	2	3	0	15327	2512
46	2	3	1	23437	5056
47	2	3	2	22977	4208
48	2	3	3	22700	3869
49	3	0	0	6463	663
50	3	0	1	14573	3207
51	3	0	2	14112	2359
52	3	0	3	13836	2019
53	3	1	0	13478	2149
54	3	1	1	21588	4693
55	3	1	2	21128	3845
56	3	1	3	20851	3506
57	3	2	0	12632	2221
58	3	2	1	20742	4765
59	3	2	2	20281	3917
60	3	2	3	20004	3578
61	3	3	0	11906	1820
62	3	3	1	20016	4364
63	3	3	2	19555	3516
64	3	3	3	19279	3177

Table 13
Notch test data of retrofitting the roof considering the HVAC retrofit.

v,k	Chiller	Heat pump	Roof	$ES^{rof}(k)$ (kWh)	$C^{rof}(k)$ ($)
1	0	0	0	0	0
2	0	0	1	81	2189
3	0	0	2	122	2790
4	0	0	3	131	11927
5	0	1	0	83	0
6	0	1	1	119	2189
7	0	1	2	137	2790
8	0	1	3	141	11927
9	0	2	0	80	0
10	0	2	1	118	2189
11	0	2	2	137	2790
12	0	2	3	141	11927
13	1	0	0	29	0
14	1	0	1	94	2189
15	1	0	2	128	2790
16	1	0	3	134	11927
17	1	1	0	112	0
18	1	1	1	132	2189
19	1	1	2	143	2790
20	1	1	3	145	11927
21	1	2	0	109	0
22	1	2	1	131	2189
23	1	2	2	142	2790
24	1	2	3	144	11927
25	2	0	0	28	0
26	2	0	1	94	2189
27	2	0	2	127	2790
28	2	0	3	134	11927
29	2	1	0	111	0
30	2	1	1	132	2189
31	2	1	2	142	2790
32	2	1	3	145	11927
33	2	2	0	108	0
34	2	2	1	130	2189
35	2	2	2	142	2790
36	2	2	3	144	11927

Table 14
Notch test data of installing one solar panel.

p	$ES^{pv}(p)$ (kWh)	$C^{pv}(p)$ ($)
1	0	0
2	393	593
3	408	870
4	402	1043

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