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Investment decision-making optimization of energy efficiency retrofit measures in multiple buildings under financing budgetary restraint

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ABSTRACT

Regarding to energy efficiency retrofit investment to numerous buildings, which buildings should be invested and which of the retrofit measures should be implemented for investable buildings are challenging tasks. The current literature have studied on choosing energy efficiency retrofit measures in single building, relatively little attention has been paid to the retrofit investment decision-making in multiple buildings. In addition, the existing studies almost put the retrofit cost as an objective that need to be minimized, and the retrofit capital budget is not taken into consideration. This paper proposes a decision-making optimization framework for energy efficiency retrofit investment in numerous buildings under financing budgetary restraint. A multi-objective optimization model with the economic goals being the net present value and time of return, and the environmental goals being the energy saving and emission reduction is presented, and then the intelligent optimization method combing particle swarm optimization and genetic algorithm is designed to search the retrofit investment strategy. The obtained investment strategy could determine which of the buildings should be invested to retrofit, and the combination of retrofitting measures for every investable building. An empirical study is conducted on 27 buildings of non-governmental organization in the state of Delaware in the United States, and the results indicate that the validity of the proposed framework. The findings indicate that the framework is an effective approach to assist the sustainability goal at regional level.

1. Introduction

According to the United Nations Environment Programme, buildings produce approximately a third of GHG emissions, and consume up to 40% of all primary energy in the world (UNEP, 2009; Si et al., 2016). The building sector is recognized as the largest consumer of primary energy, compared to other major sectors such as industry and transportation (Butler, 2008; Pérez-Lombard et al., 2008). In the United States, buildings are also the major consumers of energy, and produce 40% of the GHG emissions (VEIC, 2013). Energy efficiency improvement in buildings has been considered as one of most effective measures to reduce carbon emissions, especially as many buildings are characterized by poor energy performance (Saidur, 2009; Spyropoulos and Balaras, 2011). The fundamental way to improve existing buildings energy efficiency is through energy efficiency retrofitting (Jafari and Valentin, 2017). 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, and other electrical appliances (Ardente et al., 2011; Chidiac et al., 2011; Wu et al., 2016). Given relatively low rates of replacement of existing buildings by new buildings, retrofitting the existing building stock has been identified as having greater potential to improve energy efficiency and reduce GHG emissions than improving standards of new buildings (Roberts, 2008; EED, 2012). Therefore, energy efficiency retrofit in buildings is vital, and also the cheapest way to meet regional (city and state) emission reduction and sustainability goals.

Energy efficiency improvement efforts in buildings can be organized in several different retrofit measures, and the cost, the payback period, the energy saving and emission reduction varies among different measures. The selection of retrofit measures for existing buildings is a complex work. The challenges may include

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Nomenclature

Decision variables

x_{ij}	with the value of 0 or 1, indicating whether or not to invest the item j of NGOi
I_i	the investment capital amount of SEU in NGOi
G_i	the investment capital amount of GOV in NGOi

Model parameters

k	the total number of NGOs
N	investment cycle
θ	annual discount rate, which is used to measure the time value of capital
I_i	the investment amount of SEU to NGOi
R_i	investment revenue of NGO i for one year
n_i	the payback period of investment of NGOi
S_i	the amount of energy saving of NGO i for one year
E_{i1} , E_{i2} , E_{i3}	the amount of emission reduction of CO_2, SO_2, NO_x in NGO i for one year
d_1 , d_2 , d_3	emission factors of CO_2, SO_2, NO_x, which are weigh values of the impact of unit CO_2, SO_2, NO_x emission on the environment
Q_{i1} , Q_{i2} , Q_{i3}	the current annual emission amount of CO_2, SO_2, NO_x in NGOi
M_1 , M_2	the capital budgetary constraints of SEU and GOV
m_1 , m_2	the minimum funding requirements of SEU and GOV investment to each NGO
p_1 , p_2	the lower bound and upper bound of the proportion of NGO investment in total investment amount in each NGO
l_i	the number of items of energy efficiency retrofit measures in NGOi
c_{ij}	the required fund of item j in NGOi
s_{ij}	the annual energy saving amount of item j in NGOi
r_{ij}	the annual energy saving revenue of item j in NGOi
e_{ij1}	the annual CO_2 emission reduction of item $j$in NGO i
e_{ij2}	the annual SO_2 emission reduction of item j in NGOi
e_{ij3}	the annual NOx emission reduction of item j in NGOi

Algorithm parameters

NP	swarm size
$G_{\max}$	the maximum number of generations
w	the inertia
c_1, c_2	cognitive and social factors
$v_{\max}$	maximum velocity
p_c	crossover rate of genetic operation
p_m	mutation rate of genetic operation

Abbreviation

GHG	greenhouse gas
SEU	the Sustainable Energy Utility
DESEU	the Delaware Sustainable Energy Utility
NGO	non-governmental organization
GOV	the state government
NPV	net present value
PSO	particle swarm optimization
GA	genetic algorithm
USD	US Dollar
mmBtu	million British thermal units

financial limitations, long payback periods, and interruptions to operation. Especially, the lack of initial capital investment is a conundrum to carry out the retrofit projects with high upfront cost (Bertone et al., 2018). This underlines the importance of having financial and procurement mechanisms in place in order to facilitate access to the capital needed to fund the project. So the financing budgetary restraint should be taken into consideration in buildings energy efficiency retrofit.

The approaches to support the decision-making of buildings energy efficiency retrofit could be categorized to multi-objective optimization (Diakaki et al., 2013; Shao et al., 2014; Karmellos et al., 2015; Penna et al., 2015; Tan et al., 2016; Ascione et al., 2017; Jafari and Valentin, 2017), cost-benefit analysis (Niemelä et al., 2016; Ortiz et al., 2016a, 2016b; Almeida and Ferreira, 2017), multi-criteria analysis (Si et al., 2016; Roberti et al., 2017), life-cycle analysis (Copiello et al., 2017; Rodrigues and Freire, 2017a). However, no matter what method it is, the existing literature have studied on energy efficiency retrofit in single building, relatively little attention has been paid to tackling energy retrofit decision-making in multiple buildings with multiple objectives and constraints.

In the decision-making process to multiple buildings, there are a large number of energy efficiency measures that could be considered to retrofit multiple buildings and it is not easy to choose the best strategy. The selection of the best combination of retrofitting measures for numerous buildings is a challenging task. The objective of the study is to explore the investment decision-making issue for buildings energy efficiency retrofit in multiple buildings under financing budgetary constraint. A case study is conducted on investing the building energy efficiency measures in NGOs under SEU mechanism. The main contributions of this paper to the existing literature are as follows. ① ***Multiple buildings considering the budgetary restraint.*** The existing literature have focused on energy efficiency retrofit in single building, and paid little attention to tackling retrofit decision-making in multiple buildings. Moreover, the financing budget should be taken into consideration in the decision-making of energy efficiency retrofit in many cases of reality. However, the total retrofit cost is usually put as an objective that need to be optimized in the existing literature (Penna et al., 2015; Tan et al., 2016; Jafari and Valentin, 2017), and the retrofit capital budget is not taken as a critical constraint. To this end, this study proposes a decision-making optimization framework for investing energy efficiency retrofit measures in multiple buildings considering the capital budget restraint. ② ***Determine the buildings with the combination of retrofitting measures.*** The proposed optimization framework could simultaneously determine the buildings that should be invested, and the combination of retrofitting measures for each investable building. With regard to energy efficiency retrofit investment in multiple buildings, there are numerous buildings candidate, we should determine which buildings should be invested and which of the retrofit measures should be implemented for every investable building, to maximize the total retrofitting benefits. To the best of our knowledge, none of the literature have studied on the above questions, and thus, those issues are investigated by proposed multi-objective optimization model and the PSO-GA algorithm in this work. ③ ***Performance evaluation.*** An empirical study is conducted on the energy efficiency measures investment to 27 NGOs buildings in state of Delaware of USA. Considering different preference of objectives, we obtain the results of three cases. The obtained results are close to optimum and diversely distributed in the Pareto front. Referring to these results, decision makers can easily choose one proper result for implementation in reality. The findings indicate that the proposed approach can assist the sustainable development goal in regional level.

The remainder of this paper is organized as follows. The literature review is presented in Section 2. In Section 3, we describe the problems and propose the decision-making optimization model for investing the energy efficiency retrofit measures. In Section 4, we present the methodology for searching the optimum retrofit strategy. In Section 5, we conduct the empirical study and obtain the results. Finally Section 6 summarizes conclusions and issues for the future works.

2. Literature review

From the beginning of this century, many countries in the world have launched a number of policies and projects to improve the energy efficiency of buildings. In the United States, the government has made the reform measures and plans to promote energy saving in building sectors. The Better Building Initiative aims to reduce energy consumption by 20% in commercial buildings by 2020 using the cost-effective retrofit measures. In Europe, Energy Performance of Buildings Directive and the Energy Efficiency Directive have been published to encourage member states to introduce relative policies for promoting retrofit renovation in buildings in a cost-effective way (Wu et al., 2016). Australia has published the Commercial Building Disclosure program to promote buildings energy efficiency by energy retrofit investment through sufficient capital budget (AGDI, 2013). Germany government has committed to reduce 80% of buildings primary energy demand by 2050 (Shao et al., 2014).

The choice of energy efficiency measures is generally complex and heterogeneous, requiring the integration of various specialties under variable conditions (Soares et al., 2017). In addition, the comprehensive evaluation of buildings energy retrofit is quite difficult, for a building and its environment are complex systems involving the effect of technology, ecology, society, comfort, and other aspects (Kaklauskas et al., 2005). There are a number of models and methods developed to support the decision-making of buildings energy efficiency retrofit, and the existing literature could be categorized as the following aspects.

Multi-objective optimization. Diakaki et al. (2013) applied the multi-objective programming to retrofit an existing building, and evaluated the quality of the retrofit alternatives. Shao et al. (2014) utilized the quality function deployment and multi-objective optimization based on NSGA-II algorithm to obtain the energy efficiency retrofit solutions in office building. Karmellos et al. (2015) developed a multi-objective mixed-integer non-linear problem to implement energy efficiency measures in a new building or retrofitting an existing building in two cities with different climate characteristics. Penna et al. (2015) combined multi-objective optimization and genetic algorithm to investigate the optimal retrofit solutions in terms of either maximum economic performance or minimum energy consumption in residential buildings. Using multi-objective optimization, Ascione et al. (2015) employed Energy Plus and genetic algorithm to evaluate the cost-optimality of energy performance in residential building. Wu et al. (2015) adopted the multi-objective neighborhood field optimization algorithm to obtain the optimal retrofit strategies in office building. Tan et al. (2016) used mathematical programming approach to select the energy efficiency measures to optimize financial or environmental benefits in university buildings. Ascione et al. (2017) proposed a multi-step and multi-objective optimization of the energy refurbishment process in an educational building. Jafari and Valentin (2017) proposed a decision making framework for residential building energy retrofit, to select optimal energy retrofitting budget and retrofitting measures. A case study of a house built in 1960s in Albuquerque, New Mexico was conducted to demonstrate the implementation of the framework.

Cost-benefit analysis. Ortiz et al. (2016a) used two-step evaluation method to get cost-optimal scheme for the energy renovation of residential buildings. Ortiz et al. (2016b) presented cost-optimal analysis to evaluate energy efficiency measures for a residential building in Catalonia considering three criteria of thermal comfort, primary energy use and global costs. Niemelä et al. (2016) discussed cost-efficient energy performance renovation measures for typical educational buildings built in the 1960s and 1970s in cold climate regions. They analyzed the impact of different energy renovation measures on the energy efficiency and economic viability in an educational building. Almeida and Ferreira (2017) investigated on the decision making process for energy related building renovation, allowing to find a cost-effective balance between energy consumption, carbon emissions and overall added value.

Multi-criteria analysis. Si et al. (2016) employed multi-criteria decision making methods to select green technologies for retrofitting the existing buildings. The applicability of analytical hierarchy process was demonstrated through the case study of a university building. Roberti et al. (2017) used analytical hierarchy process to quantify conservation compatibility, and employed multi-objective optimization and genetic algorithm to identify optimal retrofits for a medieval building in the north of Italy.

Life-cycle analysis. Copiello et al. (2017) applied life-cycle cost and Monte Carlo simulation to evaluate energy retrofit under the conditions of uncertainty in a public building. Rodrigues and Freire (2017a) combined environmental life-cycle assessment, life-cycle cost and thermal dynamic simulation to assess the performance of retrofit strategies for historic buildings in Southern European climates.

Expect the above methods, Wu et al. (2016) used an optimal control approach to design the energy efficiency retrofitting strategy for the large-scale building. The optimal strategy could determine which building and which facility should retrofit at each year. Mikucioniene et al. (2014) employed sequential prioritization and decision tree to distribute the energy efficiency measures, and conducted a case study by a public building in Lithuania. Kontokosta (2016) explored the decision incentives and motivations to implement energy retrofit in commercial buildings through a survey of 763 office buildings in nineteen cities. Bertone et al. (2018) developed Bayesian network–system dynamics model to assess the influence of the novel financing options and procurement procedures on public building retrofit, and case study was conducted on Australian public hospitals.

From the above literature, we can see that the approaches based on multi-objective optimization have been widely used, because that they could consider a number of building retrofit options defined by the constraints and grasp the trade-offs between the objective functions to reach a satisfactory compromise solution (Soares et al., 2017). In the multi-objective optimization models, multiple nonlinear objectives and constraints could make the solving process very difficult and time-consuming. In this case, intelligent optimization techniques, such as genetic algorithm, have been used to solve those problems (Hamdy et al., 2011; Wright et al., 2002; Shao et al., 2014; Penna et al., 2015; Ascione et al., 2015; Roberti et al., 2017; Bahrami et al., 2018).

However, to the best of our knowledge, all of the above researches have focused on single building to choice the energy efficiency retrofit measures, and none of the studies have tackled the decision-making issues of energy efficiency retrofit in multiple buildings with multiple objectives and constraints. Moreover, there are few researches considering the financing mechanism at regional level. Generally, the existing studies have taken the total retrofit cost as an objective that need to be minimized, the retrofit capital source or constraints have not been taken into consideration. However, the capital source is of vital importance if the retrofit activities would be implemented in reality, especially for the public buildings with insufficient funds and limited retrofit incentives. So the financing mechanism should be further considered in energy efficiency retrofit decision making in many cases of reality.

In order to fill the above gaps, we will explore the issues of energy efficiency retrofitting in multiple building considering the constraint of capital budget at regional level through the case study of investing to numerous NGOs under the SEU mechanism in the state of Delaware (USA). Based on multi-objective model and intelligent optimization techniques, this study provides a decision-making optimization framework for investing to numerous NGO buildings under SEU financing mechanism, and the schematic diagram is presented in Fig. 1 that is illustrated in detail in the following sections.

3. The problem statement and model

The Sustainable Energy Utility (SEU) is an innovative public-private partnership for promoting energy efficiency improvement, load reduction and clean energy services (SEU, 2018a). The Delaware Sustainable Energy Utility (DESEU) is a non-profit organization formed to bring energy efficiency and renewable energy to the state of Delaware in USA. Its investment in Delaware's in-state clean energy and energy efficiency resources serves to strengthen local economy, create jobs, improve the environment, and ensures that Delaware has sustainable energy resource for current and future generations (SEU, 2018b). SEU has joined with the DCIC (Delaware Community Investment Corporation) and its member banks in establishing a low interest loan fund to assist non-profits and housing providers in low and moderate-income communities. This is a low-interest revolving loan fund that finances the implementation of energy efficiency measures. In conjunction with the local state government, the SEU is funding energy efficiency retrofit for non-profits and governmental agencies. The previous surveys have been done to determine what energy efficiency retrofit measures of all NGOs buildings have been recommended.

The choice of energy efficient measures in buildings could be modeled as an optimization problem, which needs to be solved through considering multiple objectives, alternatives, and constraints. However, the optimization problem has the following characteristics: first, the choice of energy efficiency retrofit measures is under the SEU mechanism, and the total capital is subjected to the financing budgetary constraint. The total capital source comes from two channels, one is from SEU and the other one is from the state government (GOV) of Delaware. Second, the DESEU is a local organization, devoted to improving energy efficiency in non-profits organizations in the state of Delaware. Third, we should not only determine which NGOs should be invested, but also need to find out the optimal combination of energy efficiency measures for each investible NGO.

Hence, in the regional level, for energy efficiency retrofit investment targeting to NGOs under the SEU mechanism, the decision-making issues include that: (i) There are numerous NGO buildings to be evaluated, whether or not to invest a special NGO building should be determined; (ii) what is the best capital amount of retrofitting investment required for a specific building, what percentage of the capital amount comes from SEU, and what percentage is from the GOV? and (iii) for a investable NGO building, which of the retrofit measures should be implemented to maximize the total retrofitting benefits? This paper aims to solve the above

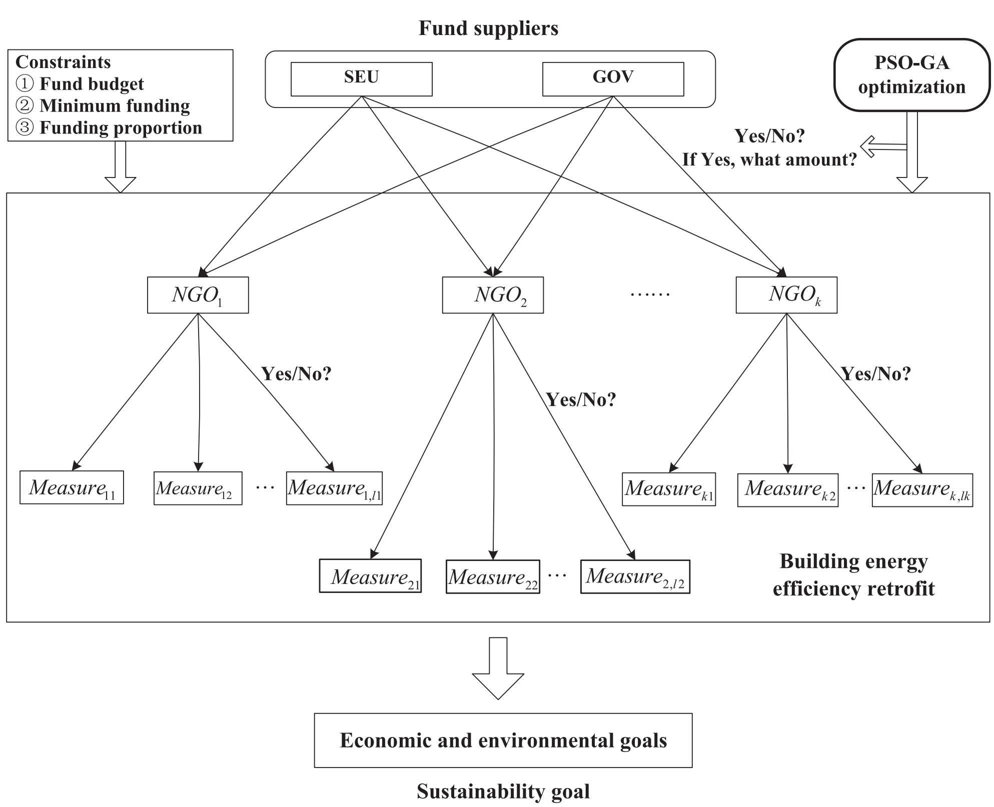

Fig. 1. Decision-making optimization framework.

issues through a decision-making framework based on multi-objective optimization model and the PSO-GA algorithm. Briefly speaking, the purpose of this study is that, under the SEU and GOV capital constraints, given all the NGOs and the alternative energy efficiency measures of each NGO, how to determine the optimal investment strategy, to maximize both of the economic and environmental goals. The multi-objective optimization model including the decision variables, goals, and constraints are described as follows.

3.1. Decision variables

$x_{ij}(i=1,\ 2\cdots k,\ j=1,\ 2\cdots l_i)$: With the value of 0 or 1, indicating whether or not to invest the item j of NGOi, here l_i is the number of items (energy efficiency retrofit measures) in NGOi;

$I_i\ \ (i=1,\ 2\cdots k)$: The investment capital amount of SEU in NGOi;

$G_i\ (i=1,\ 2\cdots k)$: The investment capital amount of GOV in NGOi.

3.2. Goals

The goals include two types, namely, economic goals and environmental goals, which are described as follows.

3.2.1. Economic goals

With regard to SEU, the economic goals is mainly two indicators, one is to maximize the net present value (NPV), the second is minimize the average payback period of investment, which are shown as Eqs. (1) and (2).

$$\max\ ECON1=\sum_{i=1}^{k}R_i\left[\frac{1-\left(\frac{1}{1+\theta}\right)^N}{\theta}\right]-\sum_{i=1}^{k}I_i \tag{1}$$

$$\min\ ECON2=\frac{1}{k}\sum_{i=1}^{k}n_i \tag{2}$$

Where k is the total number of NGOs; $N$is the investment cycle; θ is annual discount rate, which is used to measure the time value of capital; I_i is the investment amount of SEU to NGOi; $R_i$is investment revenue of NGO i for one year; n_i is the payback period of investment of NGOi.

3.2.2. Environmental goals

The environmental objective contains two goals, the first is to maximize the annual total energy saving; the second is to maximize the emission reduction rate of pollution gas for each year, which is to measure the indicator of reducing the environmental pollution. The emission reduction rate is represented by the ratio of annual emission reductions to annual total emissions amount. The goals are shown in Eqs. (3) and (4).

$$\max\ ENV1=\sum_{i=1}^{k}S_i \tag{3}$$

$$\max\ ENV2=\frac{d_1\sum_{i=1}^{k}E_{i1}+d_2\sum_{i=1}^{k}E_{i2}+d_3\sum_{i=1}^{k}E_{i3}}{d_1\sum_{i=1}^{k}Q_{i1}+d_2\sum_{i=1}^{k}Q_{i2}+d_3\sum_{i=1}^{k}Q_{i3}} \tag{4}$$

whereS_i is the amount of energy saving of NGO i for one year; E_{i1} , E_{i2} , E_{i3} are the amount of emission reduction of CO_2, SO_2, NO_x in NGO i for one year, respectively; d_1 , d_2 , d_3 are the emission factors of CO_2, SO_2, NO_x, respectively, which are weigh values of the impact of unit CO_2, SO_2, NO_x emission on the environment; Q_{i1} , Q_{i2} , Q_{i3} are the current annual emission amount of CO_2, SO_2, NO_x in NGOi, respectively.

3.3. Constraints

A. First, in the investment cycle, the limitation of investment funds in SEU and GOV are as shown in Eqs. (5) and (6).

$$\sum_{i=1}^{k}I_i\le M_1 \tag{5}$$

$$\sum_{i=1}^{k}G_i\le M_2 \tag{6}$$

where M_1 , M_2 are the capital budgetary constraints of SEU and GOV, respectively.

B. Second, for each NGO, the fund from SEU and GOV should be more than the given threshold value. The NGO could be invested only if the investment from SEU and GOV is more than respective threshold value, and the expression is shown in Eqs. (7) and (8).

$$I_i\ge m_1\ \ if\ \ I_i\ne 0 \tag{7}$$

$$G_i\ge m_2\ \ if\ \ G_i\ne 0 \tag{8}$$

where m_1, m_2 are the minimum funding requirements of SEU and GOV investment to each NGO, respectively.

C. For each NGO, the proportion of investment amount from SEU in the total investment should be within the given interval, shown in Eq. (9).

$$p_1\le\frac{I_i}{I_i+G_i}\le p_2 \tag{9}$$

where p_1 , p_2 are the lower bound and upper bound of the proportion of NGO investment in total investment amount in each NGO.

D. For each NGO, the total investment amount is equal to the summation of funds from GOV and SEU, shown in Eq. (10).

$$\sum_{j=1}^{l_i}c_{ij}x_{ij}=I_i+G_i \tag{10}$$

Where l_i is the number of energy efficiency retrofit measures in NGOi; c_{ij} is the required fund of item j in NGOi.

E. For each NGO, the annual energy savings is as shown in Eq. (11).

$$S_i=\sum_{j=1}^{l_i}s_{ij}x_{ij} \tag{11}$$

Where s_{ij} is the annual energy saving amount of item j in NGOi.

F. For each NGO, the annual revenue from energy-saving and emission-reduction investment is as shown in Eq. (12).

$$R_i=\sum_{j=1}^{l_i}r_{ij}x_{ij} \tag{12}$$

where r_{ij} is the annual energy saving revenue of item j in NGOi.

G. For each NGO, the payback period of investment is as shown in Eq. (13).

$$n_i = \log_{\frac{1}{1+\theta}}\left(1-\theta\frac{I_i}{R_i}\right) \tag{13}$$

H. For each NGO, the annual emission reduction of CO_2, SO_2 and NOx are shown in Eq. (14)–(16), respectively.

$$E_{i1} = \sum_{j=1}^{l_i} e_{ij1}x_{ij} \tag{14}$$

$$E_{i2} = \sum_{j=1}^{l_i} e_{ij2}x_{ij} \tag{15}$$

$$E_{i3} = \sum_{j=1}^{l_i} e_{ij3}x_{ij} \tag{16}$$

where e_{ij1} is the annual CO_2 emission reduction of item j in NGO i; e_{ij2} is the annual SO_2 emission reduction of item j in NGOi; and e_{ij3} is the annual NOx emission reduction of item j in NGOi. For all the above i,j, met $i=1,\ 2\cdots k,\ j=1,\ 2\cdots l_i$.

3.4. Model conversion

Let the proportion of SEU investment in total investment amount $y_i = \frac{I_i}{I_i+G_i}$, together with Eq. (10), the investment amount from SEU and GOV in each NGO are exhibited as Eq. (17) and (18) showed.

$$I_i = \left(\sum_{j=1}^{l_i} c_{ij}x_{ij}\right)y_i \tag{17}$$

$$G_i = \left(\sum_{j=1}^{l_i} c_{ij}x_{ij}\right)(1-y_i) \tag{18}$$

Combined with Eqs. (1)–(9) and Eq. (11)–(18), the Model (1–16) could be converted to the following model, which is shown in Eq. (19)–(28).

$$\max\ ECON1 = \sum_{i=1}^{k}\left(\sum_{j=1}^{l_i} r_{ij}x_{ij}\left[\frac{1-\left(\frac{1}{1+\theta}\right)^N}{\theta}\right] - \left(\sum_{j=1}^{l_i} c_{ij}x_{ij}\right)y_i\right) \tag{19}$$

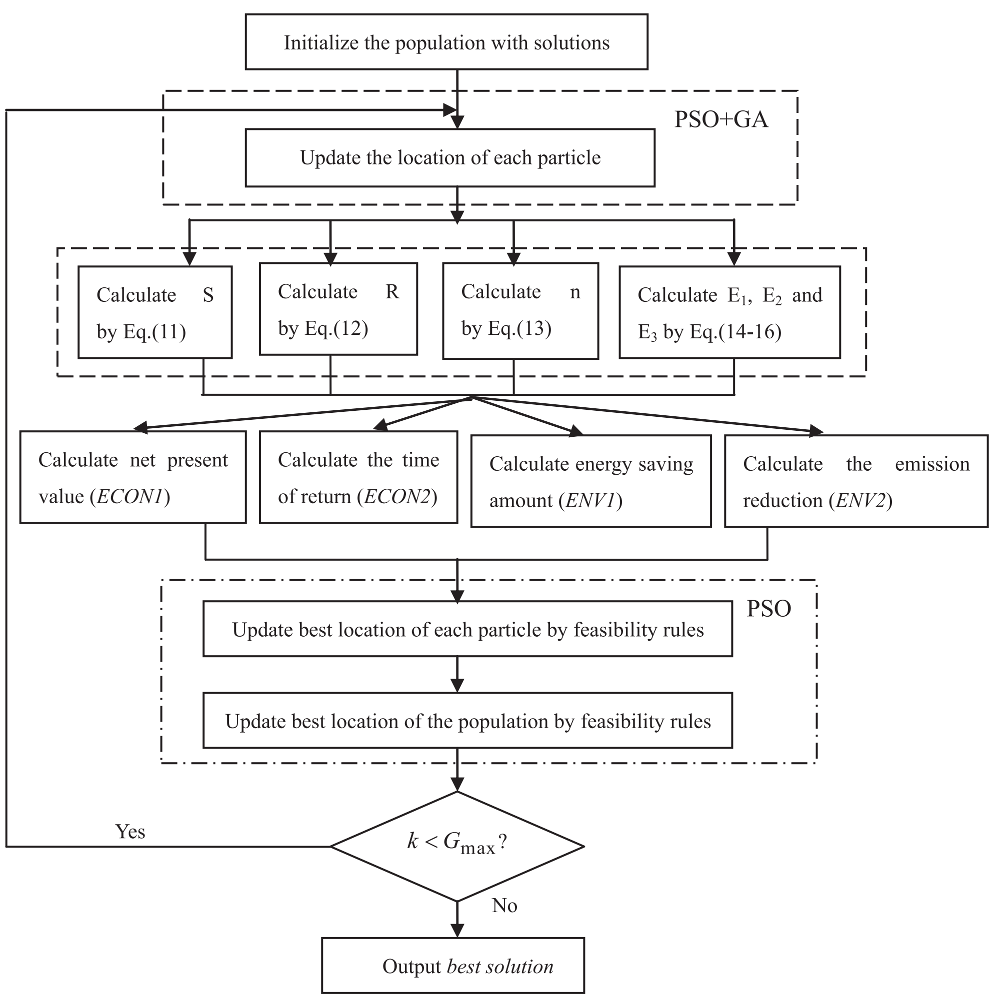

Fig. 2. The flowchart of the PSO-GA algorithm.

$$\min\ ECON2 = \frac{1}{k}\sum_{i=1}^{k}\log_{\frac{1}{1+\theta}}\left(1-\theta\frac{\sum_{j=1}^{l_i} c_{ij}x_{ij}y_i}{\sum_{j=1}^{l_i} r_{ij}x_{ij}}\right) \tag{20}$$

$$\max\ ENV1 = \sum_{i=1}^{k}\sum_{j=1}^{l_i} s_{ij}x_{ij} \tag{21}$$

$$\max\ ENV2 = \frac{\sum_{i=1}^{k}\sum_{j=1}^{l_i}(d_1e_{ij1}+d_2e_{ij2}+d_3e_{ij3})x_{ij}}{\sum_{i=1}^{k} d_1Q_{i1}+d_2Q_{i2}+d_3Q_{i3}} \tag{22}$$

$s.t$

$$\sum_{i=1}^{k}\left(\sum_{j=1}^{l_i} c_{ij}x_{ij}\right)y_i \le M_1 \tag{23}$$

$$\sum_{i=1}^{k}\left(\sum_{j=1}^{l_i} c_{ij}x_{ij}\right)(1-y_i) \le M_2 \tag{24}$$

$$\left(\sum_{j=1}^{l_i} c_{ij}x_{ij}\right)y_i \ge m_1 \ if \ \left(\sum_{j=1}^{l_i} c_{ij}x_{ij}\right)y_i \ne 0 \tag{25}$$

$$\left(\sum_{j=1}^{l_i} c_{ij}x_{ij}\right)(1-y_i) \ge m_2 \ if \ \left(\sum_{j=1}^{l_i} c_{ij}x_{ij}\right)(1-y_i) \ne 0 \tag{26}$$

$$p_1 \le y_i \le p_2 \tag{27}$$

$$x_{ij} = 0 \ or \ 1,\ \ y_i \ge 0 \ \ (i=1,\ 2\cdots k,\ j=1,\ 2\cdots l_i) \tag{28}$$

4. The methodology

The above model (19–28) is not only a constrained optimization model, but also a multi-objective optimization problem. The decision variables contain two types, one is real variables, and the other one are 0–1 variables. The traditional analytical methods for solving nonlinear constrained optimization model, including grid method, random test method, the gradient projection method, penalty function method, and two quadratic programming, could not solve this model. However, intelligent optimization methods have great advantage to solve the problem. In order to solve the above model, the particle swarm optimization (PSO) and genetic algorithm (GA) are fused to PSO-GA algorithm, to search the optimum under the nonlinear constraints. In the following, the PSO-GA algorithm is introduced in detail.

Here the particle swarm optimization and genetic algorithm are combined to find out optimal energy efficiency investment strategy of SEU and GOV to each NGO. The PSO-GA algorithm use the 0–1 encoding and real number encoding, 0–1 encoding is corresponding to the 0–1 investment decision variables x_{ij} (whether to invest item j in NGO i), the real number encoding is corresponding to y_i (the proportion of SEU investment in total investment of NGO i). The basic idea is that, x_{ij} and y_i are put as the individuals for evolutionary computation, which include 0–1 encoding and real number encoding; particle swarm optimization and genetic algorithm are utilized to find out the investment scheme that maximize the fitness function. The particle swarm optimization is put as the main search algorithm, the crossover and mutation operation in genetic algorithm is used to update the individual location of the 0–1 encoding part. The brief flowchart of PSO-GA algorithm is shown in Fig. 2, and the specific steps are as follows.

(1) Input the constants and parameters of model (19–28): The capital restricts of SEU and GOV M_1 ,M_2 ; minimum capital requirement m_1 ,m_2 ; the lower bound and upper bound of proportion of SEU investment in total investment, p_1 ,p_2 ; the number of NGO k; the number of items in NGOi, l_i; the investment amount c_{ij}; annual energy saving s_{ij}; annual energy saving revenue r_{ij}; the annual emission reduction of CO_2, SO_2 and NOx e_{ij1},e_{ij2},e_{ij3}; investment cycle N; annual discount rate of capital θ; the emission weight factors of CO_2, SO_2 and NOx, d_1 ,d_2 ,d_3 ; annual emission amount of CO_2, SO_2 and NOx, Q_{i1} ,Q_{i2} ,Q_{i3} ;

Input the parameters of PSO-GA algorithm: swarm size NP, the inertia w, cognitive and social factors c_1,c_2, the maximum number of generations $G_{\max}$, crossover rate of genetic operation p_c, and mutation rate p_m.

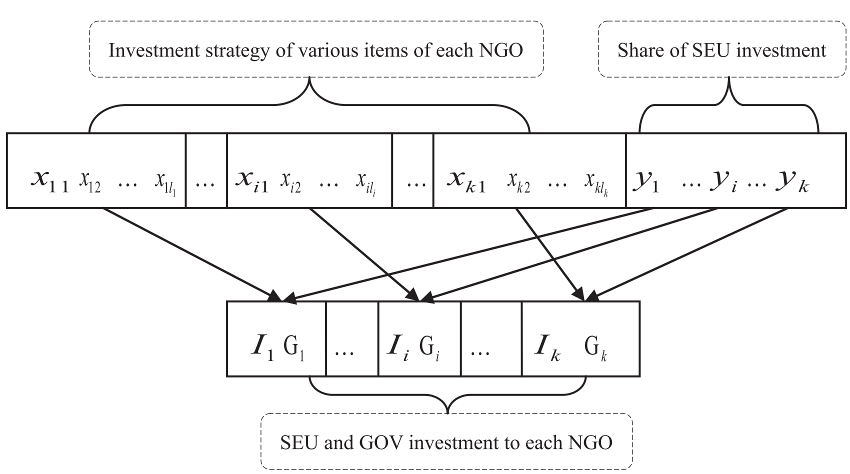

Fig. 3. Coding pattern of each individual.

(2) Initialize of the population, the best locations of each particle and the swarm. The coding pattern of each particle X is as Fig. 3 showed, here $X = [x_{ij}, y_i]$, x_{ij} $(i = 1,2,\cdots k, j = 1,2,\cdots l_i)$ is the part that adopts the 0–1 binary coding, $y_i (i = 1,2,\cdots,k)$ is the part that adopts real coding. Initialize evolving generation T = 1.

(3) For corresponding investment strategy of each individual, calculate the energy saving S_i, revenue R_i, payback period-n_i and the emission reduction $E_{i1} E_{i2}, E_{i3}$ according to Eq.(11)–(16)

(4) Calculate evaluation value of the economic goals (ECON1 and ECON2) and environmental goals (ENV1 and ENV2), furthermore, compute the fitness value of individual t at generation T, $fitness(X_t^T)$ $(t = 1,2,\cdots,NP,\ T = 1,2,\cdots G_{max})$ according to Eq. (29).

$$fitness(X) = w_1 \frac{\mathrm{ECON1}(X)}{\max\limits_{X \in \psi} \mathrm{ECON1}(X)} - w_2 \frac{\mathrm{ECON2}(X)}{\max\limits_{X \in \psi} \mathrm{ECON2}(X)} + w_3 \frac{\mathrm{ENV1}(X)}{\max\limits_{X \in \psi} \mathrm{ENV1}(X)} + w_4 \frac{\mathrm{ENV2}(X)}{\max\limits_{X \in \psi} \mathrm{ENV2}(X)} \tag{29}$$

Here, $w_j (j = 1,2,\cdots,4)$ are the weight values of various goals. ψ is corresponding possible set.

(5) To judge the feasibility, if feasible, let flag = 1, if not feasible, let flag = 0.

$$
\begin{array}{l}
if\ \sum_{i=1}^{k} I_i(X_t^T) \le \mathrm{M}_1\ and\ \sum_{i=1}^{k} \mathrm{G}_i(X_t^T) \le \mathrm{M}_2\ and\ I_i(X_t^T) \ge \mathrm{m}_1\ and\ G_i(X_t^T) \ge \mathrm{m}_2\ then \\
//\ X_t^T\ \text{is the location of individual}\ t\ \text{at generation}\ T \\
\quad flag = 1 \qquad //\ X_t^T\ \text{is feasible} \\
else\quad flag_t = 0 \qquad //\ X_t^T\ \text{is not feasible} \\
end \\
if\ \sum_{i=1}^{k} I_i(p_t^{T-1}) \le \mathrm{M}_1\ and\ \sum_{i=1}^{k} \mathrm{G}_i(p_t^{T-1}) \le \mathrm{M}_2\ and\ I_i(p_t^{T-1}) \ge \mathrm{m}_1\ and\ G_i(p_t^{T-1}) \ge \mathrm{m}_2\ then \\
//\ p_t^{T-1}\ \text{is the best location of individual}\ t \\
\quad flag = 1 \qquad //\ p_i^{T-1}\ \text{is feasible} \\
else\quad flag_p = 0 \qquad //\ p_i^{T-1}\ \text{is not feasible} \\
end \\
if\ \sum_{i=1}^{k} I_i(p_{gbest}) \le \mathrm{M}_1\ and\ \sum_{i=1}^{k} \mathrm{G}_i(p_{gbest}) \le \mathrm{M}_2\ and\ I_i(p_{gbest}) \ge \mathrm{m}_1\ and\ G_i(p_{gbest}) \ge \mathrm{m}_2\ then \\
//\ p_{gbest}\ \text{is the best location of swarm} \\
\quad flag = 1 \qquad //\ p_{gbest}\ \text{is feasible} \\
else\quad flag_g = 0 \qquad //\ p_{gbest}\ \text{is not feasible} \\
end
\end{array}
$$

(6) As the model contains constraints (5–8), the constraint handling technique based on feasible rules are used to update the history best location of each individual, and the constraint violation value of an individual is calculated as follows:

$$viol(X) = \max\left\{\sum_{i=1}^{k} I_i(X) - M_1,\ 0\right\} + \max\left\{\sum_{i=1}^{k} G_i(X) - M_2,\ 0\right\} + \sum_{i=1}^{k} \max\{m_1 - I_i(X),\ 0\} + \sum_{i=1}^{k} \max\{m_2 - G_i(X),\ 0\} \tag{30}$$

The implementation is as follows.

$$
\begin{array}{l}
if\ \ flag_i = 1\ and\ \ flag_p = 1\ and\ \ fitness(X_t^T) > fitness(p_t^{T-1}) \\
\quad then\ \ p_t^T = X_t^T \\
\quad if\ \ flag_i = 1\ and\ \ flag_p = 0 \\
\quad then\ \ p_t^T = X_t^T \\
\quad if\ \ flag_i = 0\ and\ \ flag_p = 0\ and\ \ viol(X_t^T) < viol(p_t^{T-1}) \\
\quad then\ \ p_t^T = X_t^T
\end{array}
$$

(7) The best location of the swarm is also updated based the feasible rules as follows.

$$
\begin{array}{l}
if\ \ flag_i = 1\ and\ \ flag_g = 1\ and\ \ fitness(X_t^T) > fitness(p_{gbest}) \\
then\ \ p_{gbest} = X_t^T \\
if\ \ flag_i = 1\ and\ \ flag_p = 0 \\
then\ \ p_{gbest} = X_t^T \\
if\ \ flag_i = 0\ and\ \ flag_p = 0\ and\ \ viol(X_t^T) < viol(p_{gbest}) \\
then\ \ p_{gbest} = X_t^T
\end{array}
$$

(8) The velocity and location of real coding part (the share of SEU investment) for each individual is updated as follows.

$$v_t^{T+1} = w^* v_t^T + c_1{}^*rand^*\left(p_t^T - y_t^T\right) + c_2{}^*rand^*\left(p_{gbest} - y_t^T\right) / \times /velocity\ updating$$

$$y_t^{T+1} = y_t^T + v_t^{T+1}\ //\text{location updating}$$

(9) The location of 0–1 coding part (investment strategy) for each individual is updated by genetic algorithm. The crossover operation is implemented between individual X_t^T and p_{gbest}, and then implemented between renewed X_t^T and p_t^T; Furthermore, the mutation operation is implemented on renewed individual X_t^T.
(10) Let $T = T + 1$, evaluate whether the termination condition is met; if Yes, then go to Step (11), if not, then return to Step (3).
(11) Output the best solution $X^* = p_{gbest}$, and calculate $ECON1(X^*)$, $ECON2(X^*)$, $ENV1(X^*)$ and $ENV2(X^*)$ of the optimal investment strategy.

5. Empirical study and results

The empirical study is implemented on 27 NGOs buildings in the state of Delaware in the United States. Based on the previous investigation and evaluation of each NGO, we acquire the relevant data of all the energy efficiency retrofit measures for each NGO building. In order to solve model (19–28), using the proposed PSO-GA algorithm, this study develops an intelligent optimization system for investment decision-making on energy efficiency improvement in NGOs buildings based on MatLab platform, the parameters of the model and algorithm are shown in Table 1. In the following, we list the results of three cases when different weight values of goals are given.

5.1. Results

5.1.1. Case 1

When the weight of the economic goals and environmental goals are equivalent, namely $(w_1, w_2, w_3, w_4) = (0.250, 0.250, 0.250, 0.250)$, intelligent optimization system for NGO energy saving and emission reduction are implemented, the violation value and the fitness value of each generation in the running process as shown in Fig. A1 and Fig. A2 in Appendix A, respectively.

The results are shown in Table 2, Table 3 and Appendix B. Table 2 presents the main indicators of inputs and outputs, Table 3 exhibits the specific investment scheme with the economic and environmental benefits for each NGO, and Appendix B list the detailed investment decision results of various energy efficiency retrofit items in each NGO.

The results indicate that, the total SEU investment amount is 952810 USD, and GOV investment amount is 363440 USD. Given a specific item of energy efficiency measure, whether or not select it are marked by figure “1” and “0”, of which “1” means this item is chosen, and “0” means this item is not chosen. For instance, The NGO1 contains 4 items of energy efficiency measures. All the 4 items are marked with “0”, which means none of the items are selected, so NGO1 should not be chosen to investment; NGO2 contains 8 items, of which the items 1,3,5,7,8 are marked with “1”, and items 2,4,6 are marked with “0”. This means that, items 1, 3, 5, 7, 8 should be chosen to invest. The investment amount is 36350 USD, in which 29080 USD (namely 80% of the investment amount) comes from SEU, and the other 7270 USD is from the GOV. In NGO2, the annual energy saving is 257.43 mmBtu, annual revenue is 8227 USD, the period of return back is 3.7923 years, annual CO_2 emission reduction is 90909 pounds, annual SO_2 reduction is 428.02 pounds, and the annual NO_x reduction is 130 pounds. The results show that most of the NGOs should be chosen to invest except for NGO1 and NGO9. For all NGOs, the net present value is 1493600 USD, average payback period is 2.7977 years, annual energy saving is 28625 mmBtu and the annual emission reduction is 16.3%.

5.1.2. Case 2

If economic goals, namely the NPV and average payback period are given more weight value, namely $(w_1, w_2, w_3, w_4) = (0.375, 0.375, 0.125, 0.125)$, the intelligent optimization system for investing NGOs energy efficiency retrofit measures is implemented. The violation value and the fitness value of each generation in the evolving process as shown in Fig. A3 and Fig. A4 in Appendix A, respectively.

The results are shown in Table 4, Table 5 and also in Appendix B. Table 4 presents the indicator value of main inputs and outputs, Table 5 exhibits the specific investment scheme and economic and environmental benefits for each NGO, and Appendix B lists the detailed investment decision of various items in each NGO.

The results of this case indicate that, the total capital amount from SEU is 881950 USD, and the capital amount from GOV is 416010. All the 4 items of NGO1 are marked with “0”, this means none of the items are selected, so NGO1 should not be chosen to investment; the items 1, 2, 3, 4, 5, 7 of NGO2 are marked with “1”, and items 6 and 8 are marked with “0”. This means that, among the 8 items, items 1, 2, 3, 4, 5, 7 should be chosen to invest. Moreover, the capital amount of NGO2 is 48950 USD, in which 50% of the capital amount (24475 USD) is from SEU, the other 50% (24475 USD) is from GOV. In NGO2, the annual energy saving is 280.74 mmBtu, the annual revenue is 9137 USD, the period of return back is 2.8341 years, annual CO_2 emission reduction is 93189 pounds, annual SO_2 reduction is 480.02 pounds, annual NOx reduction is 139 pounds. The results show that most of the NGOs should be invested except for NGO1 and NGO9. For all those NGOs, the net present value is 1566800 USD, average payback period is 2.6231 years, annual energy saving is 28367 mmBtu, and annual emission reduction is 15.605%.

5.1.3. Case 3

When we give preference on environmental goals, the weight values of four goals $(w_1, w_2, w_3, w_4) = (0.125, 0.125, 0.375, 0.375)$, the proposed intelligent optimization for investing energy efficiency retrofit measures in NGOs are implemented, in the running process, the violation value and the fitness value of each generation are shown in Fig. A5 and Fig. A6 in Appendix A, respectively.

The results are shown in Table 6, Table 7 and Appendix B. Table 6 presents the indicator value of main inputs and outputs, Table 7 exhibits the specific investment scheme, together with the economic and environmental benefits for each NGO, and Appendix B lists the detailed investment strategy of various items in each NGO. In this Case, with regard to all the NGOs, the total investment amount from SEU is 959020 USD, and investment amount from GOV is 493730. All the 4 items of NGO1 are marked with “0”, this means that no items are selected, thus NGO1 should not be invested; In NGO2, the result shows that items 1,3,8 among the 8 items are marked with “1”. So items 1,3,8 should be chosen to invest. The capital amount of NGO2 is 35450 USD, in which 80% of the investment amount is from SEU, and the other 20% comes from GOV. Regarding to NGO2, the annual energy saving is 249.81mmBtu, the annual revenue is 7487 USD, the period of return back is 4.081 years, annual CO_2 emission reduction is 83068 pounds, annual SO_2 reduction is 412 pounds, and annual NO_x reduction is 122 pounds. The results show that, except for NGO1 and NGO9, most of the NGOs should be chosen to invest. For all those NGOs, the net present value is 1595000 USD, the average payback period is 3.2134 years, the annual energy saving is 30171 mmBtu, and the annual emission reduction is 16.584%.

5.2. Discussion

It could be seen that the results of three cases with the goals

Table 1
The parameters of the proposed model and PSO-GA algorithm.

	Parameters	Notation	Value
Model (19–28)	SEU capital restriction (USD)	M_1	1,000,000
	GOV capital restriction (USD)	M_2	500,000
	SEU investment threshold (USD)	m_1	10,000
	GOV investment threshold (USD)	m_2	1,000
	Lower bound of SEU investment ratio	p_1	0.5
	Upper bound of SEU investment ratio	p_2	0.8
	NGO amount	k	27
	Investment cycle (year)	N	5
	The discount rate	θ	0.03
	CO_2 emission factor	d_1	1
	SO_2 emission factor	d_2	100
	NOx emission factor	d_3	200
PSO-GA algorithm	Polulation size	NP	1000
	Maximum number of generations	$G_{\max}$	200
	The inertia factor	w	Linearly decrease from 0.9 to 0.1
	Cognitive factor	c_1	2
	Social factor	c_2	2
	Maximum velocity	$v_{\max}$	0.2
	Crossover rate	p_c	0.8
	Mutation rate	p_m	0.2
	Maximum of NPV	max $ECON1$	2,000,000
	Maximum of payback period	max $ECON2$	10
	Maximum of energy-saving	max $ENV1$	50,000
	Maximum of emission reduction rate	max $ENV2$	0.2
	Weight value of objective functions	(w_1, w_2, w_3, w_4)	(0.250, 0.250, 0.250, 0.250)
			(0.375, 0.375, 0.125, 0.125)
			(0.125, 0.125, 0375, 0.375)

Table 2
Inputs and output indicators.

Inputs/Outputs	Indicators	Notation	Value	Normalization Value
SEU/GOV investment	SEU investment amount	$\sum_i I_i$	952810	–
	GOV investment amount	$\sum_i G_i$	363440	–
Economic/Environmental goals	Net present value	ECON1	1493600	0.74681
	Average payback period	ECON2	2.7977	0.27977
	Annual energy saving	ENV1	28625	0.57249
	Annual emission reduction	ENV2	0.163	0.81501
Fitness function value	Best fitness value	Fitness	0.46363	–

having different weight values are nearly the same. The results of three cases all show that most of the NGOs should be chosen to invest except for NGO1 and NGO9. But energy efficiency retrofit measures in specific NGO are different. The economic and environmental objective values of three different cases are presented in Fig. 4. Compared to Case 1 (weight values of objectives: 0.250,0.250,0.250,0.250), in Case 2 (weight values of objectives: 0.375, 0.375, 0.125, 0.125), as more weight values are given to the goals of the NPV and payback period, the NPV of Case 2 is larger than Case 1, the average payback period of Case 2 is smaller than Case 1, the annual energy saving of Case 2 is a little smaller than Case 1, the annual emission reduction of Case 2 is smaller than Case 1.

In Case 3 (weight values of objectives: 0.125, 0.125, 0.375, 3.375), since more weight values are given to the goals of the annual energy saving and annual emission reduction, the average payback period of Case 3 is larger than Case 1, the annual energy saving of Case 3 is larger than Case 1, annual emission reduction of Case 3 is larger than Case 1. However, the NPV of Case 3 is larger than Case 1. If the goal of ECON1 is measured by the ratio of economic output to economic input, the comparison of the objective values of three different cases are presented in Fig. 5. We can see that the investment schemes of three cases are non-dominated solutions in the Pareto front. It should be pointed out that, we could obtain the corresponding investment strategy if different weight values were given to the four objectives using the proposed intelligent optimization system.

In this paper, the investment decision-making problem of energy retrofitting in multiple buildings under SEU mechanism has been modeled as a multi-objective optimization problem considering NPV, time of return, energy saving and emission reduction as goals, and several optimal schemes for energy efficiency retrofit are obtained using the PSO-GA algorithm. The benefit of using PSO-GA is that the obtained scenarios are close to optimum and diversely distributed in the Pareto front. Referring to these scenarios, decision makers can easily use such comprehensive information to choose one proper scenario for implementation in reality.

The research findings validate that improving the energy efficiency of the existing building stock is an effective measure to reducing building energy consumption and carbon emissions (Sun et al., 2018). Generally speaking, assessment of the retrofit alternatives is carried out from sustainability perspective covering three aspects of environmental, economic and social goals (Liu et al., 2018). It is crucial to consider both the economic and environmental perspective of this work in support of a comprehensive retrofit decision process (Rodrigues and Freire, 2017b). The high

Table 3
Investment strategy and economic/environmental benefit for each NGO.

NGO	Investment amount (C_i)	SEU ratio (y_i)	SEU investment (I_i)	GOV investment (G_i)	Annual energy saving (S_i)	Annual revenue (R_i)	Payback period (n_i)	Annual CO_2 emission reduction (E_{i1})	Annual SO_2 reduction (E_{i2})	Annual NOx reduction (E_{i3})
1	0	0	0	0	0	0	0	0	0	0
2	36350	0.8	29080	7270	257.43	8227	3.7923	90909	428.02	130
3	61414	0.8	49131	12283	880.68	25483	2.0156	253590	1310	380
4	53140	0.8	42512	10628	716.09	18185	2.46	207660	1074.4	317.44
5	22478	0.8	17982	4495.6	1566.1	16139	1.1502	244570	534	267
6	125320	0.8	100260	25064	908.94	28155	3.822	315360	1818	501
7	23440	0.5	11720	11720	166.72	7621	1.598	60075	351.8	97.72
8	20600	0.8	16480	4120	291.37	11830	1.4443	157070	1070	272
9	0	0	0	0	0	0	0	0	0	0
10	24625	0.5	12313	12313	348.26	7385	1.7359	59669	164	70
11	18663	0.8	14930	3732.6	114.63	4045	3.9703	41308	243	67
12	75820	0.5	37910	37910	2108.8	79476	0.48762	1209500	1459.8	1159
13	18195	0.8	14556	3639	468.01	12000	1.2541	74992	102	88
14	23930	0.5	11965	11965	325.67	6235	2.006	81374	376	116
15	18050	0.8	14440	3610	161.56	2740	5.8222	37775	164	52
16	28430	0.5	14215	14215	338.7	2039	7.9382	54269	120	60
17	34151	0.8	27321	6830.2	284.17	5444	5.5203	56666	208	74
18	14520	0.8	11616	2904	658.22	14265	0.83672	155170	677	219
19	24070	0.5	12035	12035	59.738	1740	7.8678	16173	79	23
20	346660	0.8	277330	69332	8264.8	109760	2.6668	1500900	4646	1824
21	72452	0.8	57962	14490	702.69	16406	3.7903	150030	588.05	202.8
22	101820	0.5	50912	50912	6814	84838	0.61462	1135000	2932.2	1312.8
23	31480	0.8	25184	6296	1324.8	18545	1.4071	285160	1131	194
24	81620	0.8	65296	16324	729.2	22550	3.0744	239640	1341	376
25	12800	0.8	10240	2560	107.99	4210	2.5633	38915	229	62
26	14395	0.8	11516	2879	347.94	11250	1.0552	125380	736	200
27	31831	0.5	15916	15916	677.91	15621	1.0502	185270	868	266

Table 4
Input and output indicators.

Inputs/Outputs	Indicators	Notation	Value	Normalization Value
SEU/GOV investment	SEU investment amount	$\sum_i I_i$	881950	–
	GOV investment amount	$\sum_i G_i$	416010	–
Economic/Environmental goals	Net present value	ECON1	1566800	0.78342
	Average payback period	ECON2	2.6231	0.26231
	Annual energy saving	ENV1	28367	0.56734
	Annual emission reduction	ENV2	0.15605	0.78026
Fitness function value	Best fitness value	Fitness	0.36387	–

reduction of energy consumption is not always profitable from a financial perspective (Pombo et al., 2016). In this study, the results could be able to well balance economic and environmental goals. Therefore, the proposed optimization framework for energy efficiency retrofit is verified to be an effective approach to obtain the sustainability goal at regional level.

6. Conclusions

This paper proposes a decision-making optimization framework for energy efficiency retrofit in numerous buildings considering the capital restraint. In the decision-making optimization framework, a multi-objective optimization model with the goals being NPV, time of return, energy saving and emission reduction is presented, and the PSO-GA algorithm is designed to obtain the optimal solutions. In the PSO-GA algorithm, the PSO and GA are combined to find out the optimal solution cooperatively. PSO is employed to update the real value part, and GA is used to update the 0–1 encoding part for candidate solutions. The constraint handling technique based on feasible rules is designed to tackle the multiple nonlinear constraints.

An empirical study is conducted on the energy efficiency measures investment to 27 NGOs buildings in state of Delaware of USA under the SEU financing mechanism. Considering different preference of objectives, we obtain the results of three cases. The results of show that most of the NGOs should be chosen to invest except for NGO1 and NGO9. Through the comparison of three results, the obtained results are close to optimum and diversely distributed in the Pareto front. Referring to these cases, decision makers can easily choose one proper scenario for implementation. Furthermore, the intelligent approach for optimizing energy efficiency measures is dynamic, namely the optimal investment strategy could be adjusted and could vary dynamically with time and space. Given the input data and parameters in Table 1, this approach automatically outputs the optimal investment strategy to assist energy efficiency retrofit decision-making. The implications for theory and practice are as follows.

In theory, the contribution of this study lies in the proposal of an intelligent decision-making approach that could obtain the optimal strategy for energy efficiency retrofits in multiple buildings under the capital budgetary restraint. The optimization approach could not only determine which buildings should be invested to retrofit along with corresponding capital amount, but also choose the optimum combination of retrofitting measures among numerous

Table 5
Investment strategy and economic/environmental benefit for each NGO.

NGO	Investment amount (C_i)	SEU ratio (y_i)	SEU investment (I_i)	GOV investment (G_i)	Annual energy saving (S_i)	Annual revenue (R_i)	Payback period (n_i)	Annual CO_2 emission reduction (E_{i1})	Annual SO_2 reduction (E_{i2})	Annual NOx reduction (E_{i3})
1	0	0	0	0	0	0	0	0	0	0
2	48950	0.5	24475	24475	280.74	9137	2.8341	93189	480.02	139
3	95738	0.5	47869	47869	1427.2	33349	1.4891	299660	1154	394
4	100750	0.5	50375	50375	1015	27255	1.9299	315360	1705.1	492.64
5	21478	0.5	10739	10739	1140.7	13174	0.83762	192030	510	222
6	40070	0.8	32056	8014	651.31	21000	1.5859	234700	1379	376
7	44920	0.5	22460	22460	335.79	8557	2.7747	76710	324.63	106.89
8	17080	0.8	13664	3416	676.37	15000	0.9374	202110	1070	307
9	0	0	0	0	0	0	0	0	0	0
10	18349	0.8	14679	3669.8	380.5	7430	2.067	63158	162	72
11	27985	0.5	13993	13993	118.28	3025	5.0541	19630	138	22
12	43350	0.8	34680	8670	738.25	67940	0.52208	1019200	1333.7	1001
13	27045	0.8	21636	5409	558.13	14730	1.5246	103680	257	132
14	23630	0.5	11815	11815	312.51	6095	2.0269	60571	208	76
15	15050	0.8	12040	3010	173.3	3030	4.2943	42005	188	59
16	28052	0.5	14026	14026	320.17	1723	9.4725	47595	81	49
17	17850	0.8	14280	3570	159.54	3406	4.5476	40472	194	59
18	14520	0.8	11616	2904	658.22	14265	0.83672	155170	677	219
19	24070	0.5	12035	12035	59.738	1740	7.8678	16173	79	23
20	351350	0.8	281080	70271	8270.1	106630	2.7871	1456100	4251	1734
21	73280	0.5	36640	36640	776.61	17265	2.2255	161580	612.08	213.8
22	82365	0.8	65885	16480	6806.1	81729	0.82822	1079100	2455.6	1200.4
23	33700	0.8	26960	6740	1333.8	19160	1.4591	288380	1150	199
24	86075	0.8	68860	17215	648.46	22580	3.246	233670	1371	375
25	13000	0.8	10400	2600	119.69	4330	2.53	40284	229	63
26	16790	0.8	13432	3358	587.94	14760	0.93645	156140	759	228
27	32505	0.5	16253	16253	818.59	17395	0.96181	206270	908	288

Table 6
Input and output indicators.

Inputs/Outputs	Indicators	Notation	Value	Normalization Value
SEU/GOV investment	SEU investment amount	$\sum_i I_i$	959020	–
	GOV investment amount	$\sum_i G_i$	493730	–
Economic/Environmental goal	Net present value	ECON1	1595000	0.79749
	Average payback period	ECON2	3.2134	0.32134
	Annual energy saving	ENV1	30171	0.60343
	Annual emission reduction	ENV2	0.16584	0.82918
Fitness function value	Best fitness value	Fitness	0.59675	–

alternatives for a specific building. This work is an important extension to the body of knowledge in the area of improving building energy efficiency. The concept of sustainable building refurbishment provides excellent opportunities to reduce energy consumption and encourages the implementation of sustainable principles including citizen's health, environment protection, rational resource use (Mickaityte et al., 2008). Sustainable building energy efficiency retrofit should consider economic vitality, environmental quality, and social equity at the project level. Current sustainable building systems for major refurbishment pay little attention to the retrofitting process and delivery business model (Xu et al., 2015). The results of the empirical study show that the investment on building energy efficiency retrofit under SEU mechanism can bring economic benefit, conserve energy resource, and improve the environment quality. So the SEU financing mechanism could be an effective business model for supporting the concept of sustainable building refurbishment (Mickaityte et al., 2008) and greening building (Yudelson, 2009), and this study has important theory contribution to the sustainability research.

In practice, the results indicate that energy efficiency retrofit in buildings is an effective way to meet regional (city and state) emission reduction and sustainability goals. The proposed optimization framework could assist the decision making on investing the energy efficiency retrofit measures in multiple buildings. In addition, the reduction of energy consumption is not always profitable from a financial perspective, and the market generally lacks of financial incentives to engage with buildings retrofit scheme (Liu et al., 2018). The findings indicate that the proposed optimization approach is an effective approach to attain the sustainability goal by taking into consideration of the interests of government, fund supplier and building owners. Hence, the findings can provide insightful information for policy makers and stakeholders to support the popularization and application in buildings energy efficiency retrofit.

Several limitations should be noted that, first, the weight values of the objectives in the proposed model need to be pre-defined by the decision makers before the PSO-GA algorithm is run to solve the multi-objective model. Since the proposed model contains four objectives and numerous variables, it is very arduous to get all Pareto solution set if the weight values of the objectives were not previously given. Second, though the proposed PSO-GA algorithm is satisfactory to find out the optimal solution for the presented multi-objective model, it still has potential to improve the running efficiency and robustness. Third, the sustainability goal should

Table 7
Investment strategy and economic/environmental benefit for each NGO.

NGO	Investment amount (C_i)	SEU ratio (y_i)	SEU investment (I_i)	GOV investment (G_i)	Annual energy saving (S_i)	Annual revenue (R_i)	Payback period (n_i)	Annual CO_2 emission reduction (E_{i1})	Annual SO_2 reduction (E_{i2})	Annual NOx reduction (E_{i3})
1	0	0	0	0	0	0	0	0	0	0
2	35450	0.8	28360	7090	249.81	7487	4.081	83068	412	122
3	115240	0.5	57619	57619	1552.7	36218	1.6544	344880	1420	466
4	82540	0.8	66032	16508	1085.3	24910	2.8034	301580	1636	471.89
5	21478	0.8	17182	4295.6	1140.7	13174	1.3503	192030	510	222
6	51220	0.8	40976	10244	759.82	24500	1.7415	273790	1609	439
7	55220	0.8	44176	11044	372.34	10234	4.6918	89878	401.74	128.31
8	62950	0.8	50360	12590	1053	20150	2.6367	275290	1323	400
9	0	0	0	0	0	0	0	0	0	0
10	31440	0.8	25152	6288	174.35	3975	7.1216	41288	181	59
11	25090	0.8	20072	5018	114.04	2870	7.9666	18105	128	19
12	87120	0.8	69696	17424	2118.7	79746	0.89886	1213100	1480.8	1164
13	27245	0.8	21796	5449	596.64	15760	1.4336	109530	262	139
14	22990	0.5	11495	11495	135.98	4005	3.0461	32976	148	46
15	22390	0.5	11195	11195	194.35	3550	3.3623	49591	233	71
16	28430	0.5	14215	14215	335.31	1989	8.1638	53050	113	58
17	33808	0.8	27046	6761.6	326.06	6480	4.5258	74060	315	103
18	14520	0.8	11616	2904	658.22	14265	0.83672	155170	677	219
19	24070	0.5	12035	12035	59.738	1740	7.8678	16173	79	23
20	335450	0.5	167730	167730	8532.8	110440	1.5776	1504300	4403	1793
21	83992	0.8	67194	16798	740.07	18714	3.8558	165690	685.05	228
22	100040	0.5	50022	50022	6911.1	85097	0.60192	1116900	2677	1261.9
23	50210	0.8	40168	10042	1374.1	20965	2.0027	302890	1236	223
24	81190	0.8	64952	16238	718.79	22380	3.0817	235890	1319	370
25	15545	0.8	12436	3109	125.77	4900	2.6792	45321	267	72
26	16465	0.8	13172	3293	358.46	11830	1.1494	129170	758	206
27	28660	0.5	14330	14330	483.19	12300	1.2036	144430	765	220

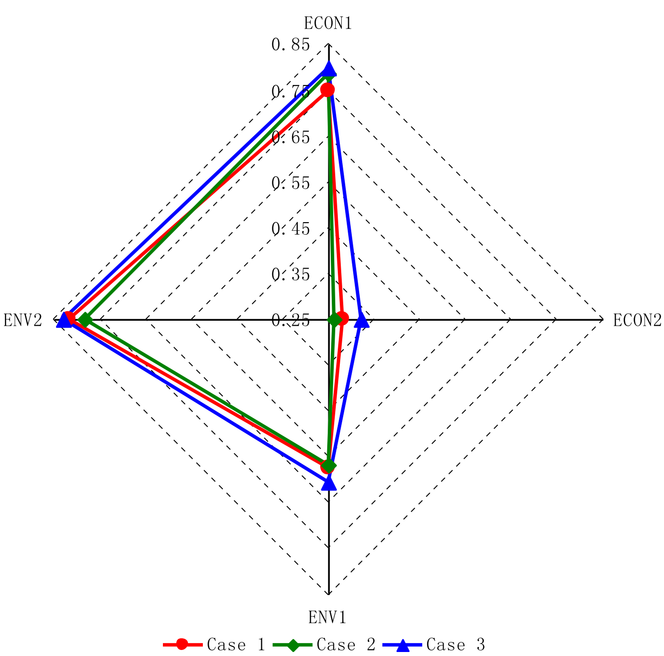

Fig. 4. Objective values of three cases.

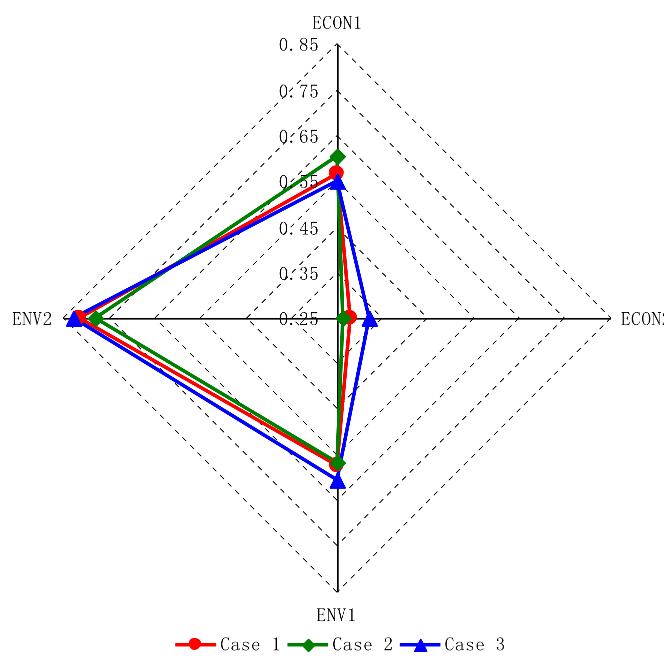

Fig. 5. Objective values comparison.

include the aspects of economy, environment and society. Since the goal of social benefit is difficult to quantify, we just consider economic and environmental goals in this study. These issues will be taken into consideration in the future works.

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Appendix A

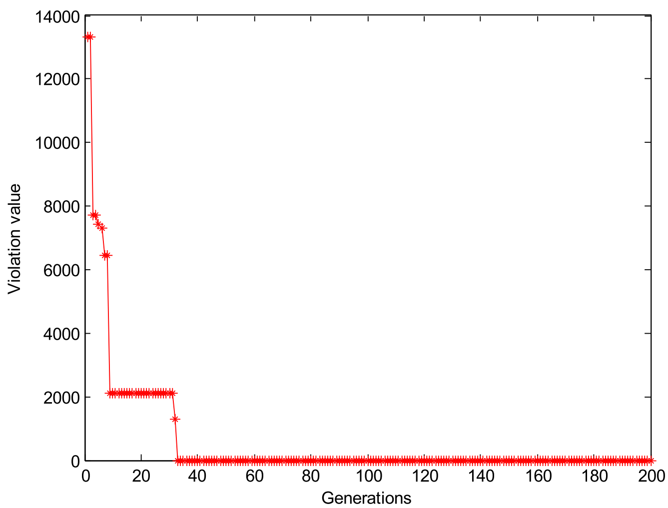

Fig. A1. The violation value in the running process in case 1.

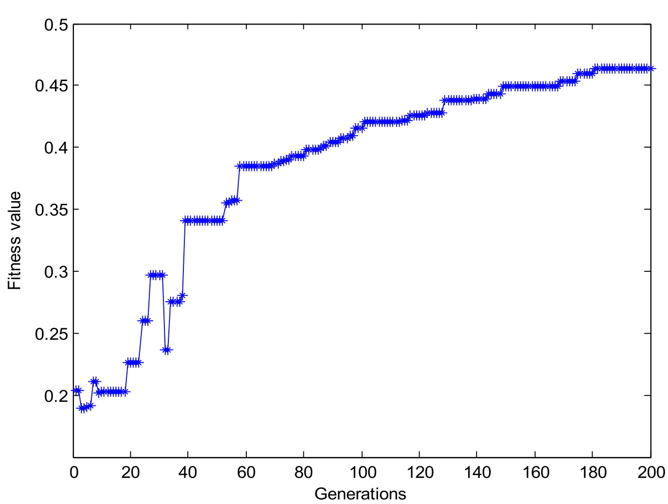

Fig. A2. The fitness value in the running process in case 1.2

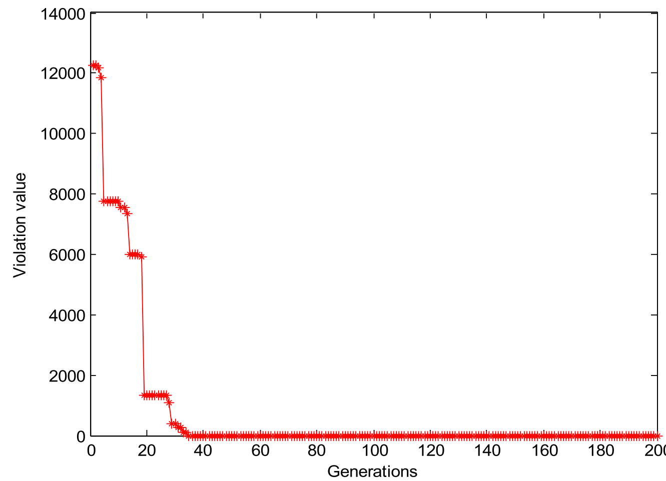

Fig. A3. The violation value in the running process in case 2.3

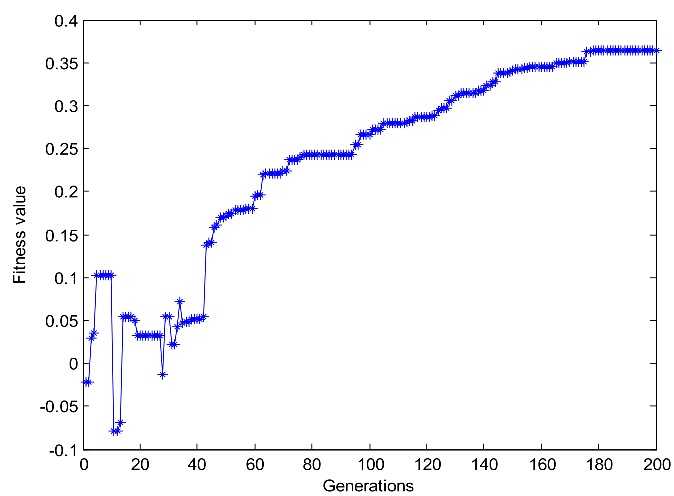

Fig. A4. The fitness value in the running process in case 2.4

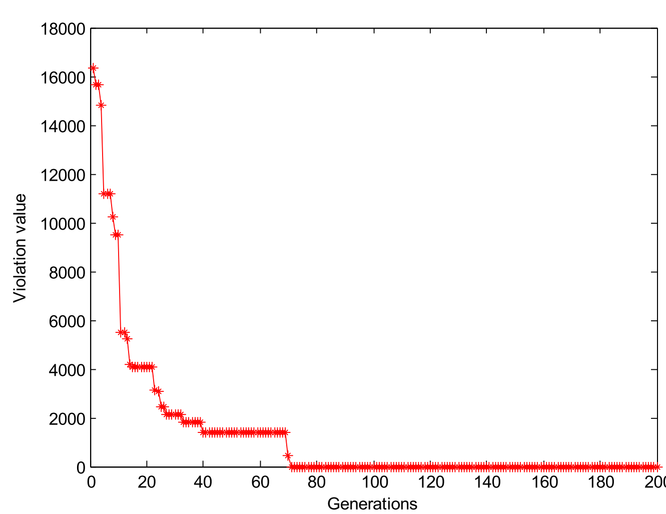

Fig. A5. The violation value in the running process in case 3.5

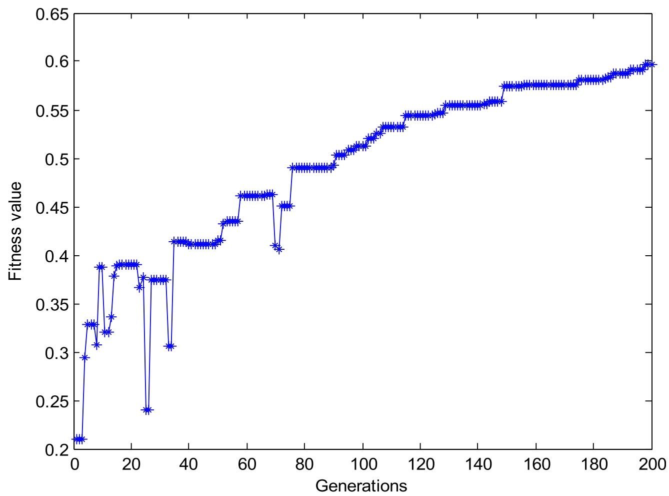

Fig. A6. The fitness value in the running process in case 3.6

Appendix B. The results of energy efficiency measures investment

(Note: "1" means this item is chosen, and "0" means this item is not chosen).

NGO label	Number of items	Items	Case 1	Case 2	Case 3
1	4	1	0	0	0
		2	0	0	0
		3	0	0	0
		4	0	0	0
2	8	1	1	1	1
		2	0	1	0
		3	1	1	1
		4	0	1	0
		5	1	1	0
		6	0	0	0
		7	1	1	0
		8	1	0	1
3	9	1	1	1	1
		2	1	0	0
		3	1	1	1
		4	1	0	1
		5	0	1	1
		6	0	1	1
		7	1	0	0
		8	1	1	1
		9	0	1	1
4	11	1	1	1	1
		2	1	1	0
		3	0	1	1
		4	1	1	0
		5	0	1	1
		6	0	1	1
		7	0	1	0
		8	1	1	0
		9	0	1	1
		10	0	0	1
		11	1	1	1
5	8	1	1	0	0
		2	1	1	1
		3	1	1	1
		4	1	1	1
		5	1	1	1
		6	0	0	0
		7	1	1	1
		8	1	1	1
6	6	1	1	1	1
		2	1	1	1
		3	0	0	1

(*continued*)

NGO label	Number of items	Items	Case 1	Case 2	Case 3
		4	0	0	0
		5	1	0	0
		6	1	0	0
7	7	1	0	1	1
		2	1	0	1
		3	1	1	1
		4	0	0	0
		5	0	1	1
		6	0	0	1
		7	0	0	0
8	10	1	0	0	1
		2	1	1	1
		3	1	1	1
		4	1	1	1
		5	0	0	1
		6	1	0	0
		7	0	1	1
		8	0	1	1
		9	0	0	1
		10	1	1	1
9	4	1	0	0	0
		2	0	0	0
		3	0	0	0
		4	0	0	0
10	11	1	1	1	0
		2	0	1	0
		3	0	1	1
		4	0	1	0
		5	1	1	0
		6	1	0	1
		7	1	0	1
		8	1	0	0
		9	0	0	1
		10	1	1	1
		11	0	1	1
11	6	1	1	1	0
		2	1	0	1
		3	1	0	0
		4	1	0	0
		5	1	1	0
		6	0	1	1
12	12	1	1	1	1
		2	1	1	1
		3	1	1	1
		4	1	0	1
		5	1	0	1
		6	0	0	0
		7	0	1	0
		8	1	0	1
		9	1	0	0
		10	0	0	1
		11	1	1	1
		12	1	0	1
13	7	1	1	1	1
		2	0	1	1
		3	1	1	1
		4	0	0	1
		5	0	1	1
		6	0	1	1
		7	1	1	1
14	8	1	1	1	0
		2	0	1	1
		3	0	1	1
		4	1	0	0
		5	1	1	1
		6	1	0	0
		7	1	1	1
		8	0	0	0
15	4	1	1	0	1
		2	0	1	1
		3	0	1	0
		4	1	1	1
16	6	1	1	0	0
		2	0	1	1
		3	1	0	1

(*continued*)

NGO label	Number of items	Items	Case 1	Case 2	Case 3
		4	1	1	1
		5	1	1	1
		6	1	1	1
17	16	1	0	0	1
		2	1	0	1
		3	1	0	0
		4	1	0	1
		5	0	1	0
		6	1	1	0
		7	1	1	1
		8	1	0	1
		9	0	0	1
		10	1	1	1
		11	1	1	0
		12	0	1	1
		13	0	0	0
		14	0	0	0
		15	0	0	0
		16	0	1	0
18	2	1	1	1	1
		2	1	1	1
19	2	1	1	1	1
		2	1	1	1
20	13	1	1	1	1
		2	1	1	1
		3	1	1	1
		4	1	0	1
		5	1	1	1
		6	1	1	1
		7	1	1	0
		8	0	1	1
		9	0	1	1
		10	1	0	1
		11	1	1	1
		12	0	1	0
		13	0	0	0
21	13	1	0	1	0
		2	1	1	1
		3	0	1	1
		4	0	0	0
		5	0	1	1
		6	1	0	1
		7	1	1	1
		8	0	0	0
		9	1	1	1
		10	0	0	0
		11	1	1	1
		12	1	1	0
		13	0	1	0
22	18	1	1	1	1
		2	0	0	1
		3	1	1	1
		4	1	1	1
		5	1	1	1
		6	1	1	1
		7	1	1	1
		8	1	1	1
		9	0	1	0
		10	1	1	1
		11	0	0	0
		12	1	1	1
		13	1	0	0
		14	1	0	0
		15	1	0	1
		16	1	0	0
		17	1	1	1
		18	1	0	1
23	12	1	1	1	1
		2	1	1	1
		3	0	0	1
		4	1	0	0
		5	0	1	1
		6	1	1	1
		7	1	1	1
		8	1	0	1

(*continued*)

NGO label	Number of items	Items	Case 1	Case 2	Case 3
		9	0	1	1
		10	0	0	1
		11	1	0	0
		12	0	0	1
24	8	1	1	0	1
		2	1	1	0
		3	0	0	0
		4	1	1	1
		5	1	1	1
		6	1	1	1
		7	0	1	0
		8	1	1	1
25	3	1	1	1	1
		2	0	0	1
		3	0	1	0
26	8	1	1	1	1
		2	0	1	0
		3	1	0	1
		4	1	1	1
		5	1	0	0
		6	0	1	1
		7	1	1	1
		8	1	1	1
27	7	1	1	1	0
		2	0	1	1
		3	1	1	0
		4	1	1	1
		5	1	1	0
		6	1	1	1
		7	1	1	1

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.01.119.

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