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Energy-efficiency building retrofit planning for green building compliance

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ABSTRACT

To promote sustainable development and expedite the progress on moving to a green building sector, the government of South Africa has developed an energy performance certificate (EPC) standard for buildings. A building is required to obtain a certain rating from the EPC in order to comply with the country's green building policy. Therefore, finding optimal retrofit plans for existing buildings are essential given the high investments involved in the retrofit of buildings that do not currently comply with the policy. This paper presents an optimization model to help decision makers to identify the best combination of retrofit options for buildings to ensure policy compliance in the most cost-effective way. The model determines optimal retrofit plans for a whole building in a systematic manner, taking into account both the envelope components and the indoor facilities. A roof top PV system is utilized to reduce the usage of electricity produced from fossil fuels. The model breaks down the long-term investment into yearly short-term investments that are more attractive to investors. Tax incentive program available in the country is taken into account to offset the long payback period of the investment. Economic analysis is also built into the model to help decision makers to make informed decisions. The retrofit of an existing office building is taken as a case study. The results show that 761.6 MWh energy savings and an A rating from the EPC can be obtained with a payback period of 70 months, which demonstrates the effectiveness of the model developed.

1. Introduction

The building sector is responsible for about 30%–40% of energy consumption throughout the world, being one of the largest energy consuming sectors [1,2]. It was also concluded that existing buildings are the main cause of the high energy consumption in the sector given that the replacement rate of existing buildings with new buildings is about 1%–3% per year [3]. In view of this, improving the energy efficiency of existing buildings is a priority task to mitigate environmental impacts of the building sectors [4]. Aligning to this purpose, many countries, such as the US, Australia, China, etc., are developing green building policies to promote the transition to a green building sector. For example, the Leadership in Energy and Environmental Design (LEED) certification program developed by the US Green Building Council, the Green Star rating system developed in Australia, and the evaluation standard for green buildings developed in China all aim to bring down the energy demand of the building sector. For the same purpose, the government of South Africa has recently developed a similar rating system called energy performance certificate (EPC) of buildings [5]. Unlike green building rating systems developed by other countries, the EPC program only focuses on the energy intensity, without considering other indicators such as water usage and indoor air quality, thus, enforcing the building sector to use energy more efficiently.

The EPC system classifies the energy intensity of a building into seven grades ranging from grade A to grade G. Grade A is for the most energy efficient buildings and grade G is for buildings that are the most inefficient. These grades are rated according to the energy intensity of a building in comparison with a reference consumption level determined for buildings of different occupancy classes specified in Ref. [6]. The national green building policy requires that all buildings which are owned, operated and leased by the South African Department of Public Works must reach at least a D rating from the EPC. Enforcement of this green building policy will be extended to all buildings in the country shortly.

While a Grade D rating is mandatory, the government is also promoting higher ratings for the targeted buildings. The existing buildings targeted are usually quite old and are inefficient. Achieving a desired rating for these buildings requires considerable investments. In light of the financial uncertainties and long payback periods of some existing building retrofit projects, a decision support tool is essential to help decision makers to come up with the optimal retrofit plan. This paper aims to fill in this gap by developing an optimization model to identify the optimal retrofit plan aiming at achieving the desired grade with the

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Nomenclature

α_1	power load densities of people (W/m^2)
α_2	power load densities of lightings (W/m^2)
α_3	power load densities of appliances (W/m^2)
$\overline{C_f}(M)$	the absolute value of the cumulative cash flow at the end of the M-th month ($)
β_t	budget allocated in year t for retrofit ($)
$\delta(t)$	coefficient taking the values from Table 1
$\Delta W(t)$	difference of humidity ratio between the inside air and outdoor air in year t (kg/kg)
η_p	efficiency of the p-th solar panel alternative
η_s	average solar energy to electrical power conversion efficiency
λ_j	thermal conductivity of the j-th alternative of the external wall insulation materials (W/m°C)
λ_k	thermal conductivity of the k-th alternative of the roof insulation materials (W/m°C)
ζ_a	allowance rate set by the government
ζ_t	tax rate for general businesses in South Africa
A_l^{pv}	area of the l-th solar panel alternative (m^2)
A_p^{pv}	area of one solar panel of the p-th alternative (m^2)
A_e	available roof area for the PV power supply system installation (m^2)
A_{flr}	areas of the floor of the building (m^2)
A_g	gross area of the building (m^2)
A_{rof}	areas of the roof of the building (m^2)
A_{wal}	areas of the walls of the building (m^2)
A_{win}	areas of the windows of the building (m^2)
C	number of chiller alternative
$C(t)$	retrofit cost in year t ($)
C_c^{chi}	cost of the c-th chiller alternative ($)
$C_f(M+1)$	the discounted cash flow in the $(M+1)$-th month ($)
C_h^{pum}	cost of the h-th heat pump alternative ($)
C_i^{win}	cost of the i-th window alternative ($/m^2)
C_j^{wal}	cost of the j-th wall insulation material alternative ($/m^2)
C_k^{rof}	cost of the k-th roof insulation material alternative ($/m^2)
C_l	latent heat factor of air (W/(L/s))
C_l^{pv}	unit cost of the l-th solar panel alternative ($)
C_s	sensible heat factor of air (W/(°C L/s))
$C_{dd}(t)$	cooling degree days in year t (°Ch)
$C_{l_m}^{lig_m}$	unit cost of the l_m-th alternative of the lightings used to retrofit the m-th type of existing lighting technologies ($)
d	discount rate
d_j	thickness of the j-th alternative of the external wall insulation materials (m)
d_k	thickness of the k-th alternative of the roof insulation materials (m)
$E_p(t)$	net energy consumed by the building in year t (kWh/m^2)
E_r	reference of net annual energy consumption (kWh/m^2)
$E_{cool}(t)$	energy consumed by the chillers in year t
$E_d(t)$	energy usage of lighting systems and appliances in year t
$E_{heat}(t)$	electrical energy used for the heating purpose in year t
$E_i(t)$	internal heat gain in year t
$E_{lc}(t)$	latent heat gain in year t
$E_{lh}(t)$	latent heat gain in year t
E_{pre}	baseline energy consumption of the building before retrofit
$E_{pv}(t)$	energy produced by the PV system in year t
$E_{sc}(t)$	sensitive heat gain in year t
$E_{sh}(t)$	sensitive heat loss in year t
$E_{sl}(t)$	solar heat gain of the cooling load in year t
$E_{tc}(t)$	transmission heat gain of the cooling load in a general building in year t
$E_{th}(t)$	transmission heat loss through the envelope in year t
$E_{tot}(t)$	total energy consumption of the building during year t
$ES(t)$	resultant energy savings in year t
H	number of heat pump alternative
$H_{dd}(t)$	heating degree days in year t (°Ch)
$HSPF(t)$	heating seasonal performance factor in year t (Btu/Wh)
$HSPF_h$	performance coefficient of the h-th heat pump alternative
I	number of window alternative
$I_{pv}(t)$	solar irradiation on the PV power supply system during year t (Wh/m^2)
$I_{win}(t)$	solar irradiance on windows in year t (W/m^2)
J	number of wall insulation material alternative
K	number of roof insulation material alternative
L_m	number of lighting alternative for retrofitting the m-th type of existing lights
M	the month after the investment at which the last negative cumulative discounted cash flow occurs
m	number of existing lightings' type
N_{l_m}	maximum quantity of the m-th type of existing lamps available for retrofit
$N_{lig_m}(t)$	number of the m-th type of existing lighting technology retrofitted in year t
$N_{pv}(t)$	number of the selected solar panel to be installed in year t
P	number of solar panel alternative
$p(t)$	electricity price in year t ($/kWh)
P_a	total power of the appliances in the building in year t (W)
$P_l(t)$	total power of the lights in the building in year t (W)
Q_s	air flow rate (L/s)
$R(t)$	the actual monetary incentive in year t
$SEER(t)$	seasonal energy efficiency ratio (Btu/Wh)
$SEER_c$	performance coefficient of the c-th chiller alternative
$SHGC(t)$	solar heat gain coefficient as a function of incident angle in year t
T	project period
$T_c(t)$	cooling time in year t (h)
$T_h(t)$	heating time in year t (h)
T_p	payback period measured (months)
$T_s(t)$	solar radiation time in year t
$T_d(t)$	occupancy time of the lightings and appliances in year t (h)
$T_{oc}(t)$	occupancy time during the cooling season in year t (h)
U_i	thermal transmittance of the i-th window alternative (W/m^2°C)
U_r	thermal transmittance of the roof before retrofit (W/m^2°C)
U_w	thermal transmittance of the wall before retrofit (W/m^2°C)
$U_{flr}(t)$	thermal transmittances of the floor in year t (W/m^2°C)
$U_{rof}(t)$	thermal transmittances of the roof in year t (W/m^2°C)
$U_{wal}(t)$	thermal transmittances of the walls in year t (W/m^2°C)
$U_{win}(t)$	thermal transmittances of the windows in year t (W/m^2°C)
w_1	positive weight
w_2	positive weight
$x_c^{chi}(t)$	retrofit state of the c-th chiller alternative in year t, similar to $x_i^{win}(t)$
$x_h^{pum}(t)$	retrofit state of the h-th heat pump alternative in year t, similar to $x_i^{win}(t)$
$x_i^{win}(t)$	retrofit state of the i-th alternative of the windows
$x_j^{wal}(t)$	retrofit state of the j-th alternative of the insulation materials for the external walls in year t, similar to $x_i^{win}(t)$
$x_k^{rof}(t)$	retrofit state of the k-th alternative of the insulation materials for the roof in year t, similar to $x_i^{win}(t)$
$x_p^{pv}(t)$	retrofit state of the p-th solar panel alternative in year t, similar to $x_i^{win}(t)$
$x_{l_m}^{lig_m}(t)$	retrofit state of the l_m-th alternative of the lightings for the m-th type of existing lightings in year t, similar to $x_i^{win}(t)$

maximum possible financial benefits.

To reduce energy usage of buildings, it is noted that energy consumption in buildings are attributed to two main subsystems. That is, the energy dissipated by the envelope/enclosure that separates the interior and exterior environments and the energy consumed by the facilities and appliances inside the building.

In the literature, the energy efficiency of buildings was classified into performance efficiency, operation efficiency, equipment efficiency, and technology efficiency, definitions of which are given in published works such as [7–9]. Efforts on improving the energy efficiency of the existing buildings, regarding the two subsystems mentioned earlier, were mainly focused on the technology and equipment efficiency levels from both power supply and demand sides. At technology efficiency level, efforts have been made to introduce renewable power generating technologies to buildings, including solar systems [10,11], wind systems [12], etc. from the energy supply side. At the same time, many energy efficiency technologies have been developed and reported from the demand side. These include development of insulation materials [13–15], energy-efficient appliances [16], etc. At the equipment level, the maintenance of envelope system, ventilation and air conditioning (HVAC) systems and lighting systems was also studied [17–20]. At the operation level, studies have been focused on the optimal scheduling, coordination, and control of the indoor appliances/facilities including heating, HVAC systems, lighting systems, smart appliances [21,22], etc. to reduce both energy consumption and cost for individual or a group of buildings. Performance level studies were mainly focusing on the impacts of existing building on the environment and the electricity grid. Such as the ones reported in Refs. [23–25].

The retrofit planning, a technology level problem, has not been well studied in the literature. Majority of the reported studies in this area focuses on developing guidelines to facilitate the retrofit process or on the cost-benefit analysis of retrofits. This means that the reported studies mostly focusing on policy or management level, that deals with long term impacts of the retrofit or the procedures of a building retrofit at a high level. For example [26], concluded that the key enabling factors for the implementation of green building retrofits include introduction of a project facilitation team, performance contracting, etc. [27] presented a state-of-the-art review of all building energy retrofit activities and developed a conceptual method for determining the most cost-effective retrofit measures for a particular project [28]. emphasized the importance of the selection of optimization objectives in the decision making process for building retrofits and developed a decision matrix to guide the objective selection process [29]. looked into developing a building retrofit index to guide the selection of building with the best retrofit potential at regional and national scales to support green building policies making use of a clustering method. Cost-benefit analysis of building retrofits was reported in Ref. [30] aiming at offer policy makers and managers to develop incentive mechanisms and management interventions to promote the implementation of building retrofit programs [31]. presented a life cycle analysis approach for building retrofits with similar objective of helping identify retrofit options in early planning stage. As pointed out by Webb in a review paper [32], echoed by another review paper [27], that although the development of building retrofit criteria, performance simulation and analysis tools, and consistent guidelines certainly aids the building retrofit process, methods to identify the most cost-effective retrofit measures for particular projects is still a major technical challenge.

In this regard, several studies presented detailed mathematical models to determine the optimal retrofit options in a building from several aspects. In particular, a mixed integer model was developed for the indoor appliances retrofit to reduce energy consumption in Ref. [33] from a control system point of view. In the building retrofit for green building certification context, a particular study [34] reported an optimization model to reduce energy and water consumptions of an existing building aiming at LEED certification. In Ref. [34], the optimal retrofit planning problem was formulated as a mixed integer programming problem, which only considered indoor appliances such as light bulbs and washing machines. Because of the envelope structure's significant contribution to a building's energy consumption, the retrofit planning for the envelope components of buildings was also studied recently in Refs. [35–37].

However, no study on the systematic retrofit planning for the whole building including the envelope and the indoor systems has been reported so far. Only indoor facilities were considered in Refs. [19,33,34]. The thermal dynamics of the building envelope, which contributes up to 40% of energy consumption of buildings, was ignored in those studies. Previous studies on the building envelope energy consumption reduction, however, didn't consider the energy usage inside the building [35–38]. Consequently, no study was done on retrofit planning considering the interactions between the indoor and envelope systems of the building in terms of energy consumption. This is because of the technical difficulties associated with the building retrofit problem considering both the envelope and indoor systems. When only indoor appliances are considered, the problem can be formulated as a linear mixed integer problem. However, the problem becomes highly nonlinear and of high-dimensional when both the indoor and envelope systems are involved. In addition, no study on the optimal building retrofit plan considering the EPC rating system, which looks at the energy intensity of a whole building and calls for a systematic whole-building retrofit approach, has been conducted.

Therefore, the purposes of this study are to

- develop a mathematical model that can determine an optimal retrofit plan for the whole building aiming at maximizing the energy savings, minimizing the payback period of the project, and achieving a desired energy rating from the EPC systematically;
- help decision makers to directly obtain the best retrofit solution to a specific building without the need of complex human decision making process;
- provide a detailed analysis of the retrofit plan given by the model developed in terms of its financial implications such as payback period, NPV, etc.

Although operational level optimization is also an important aspect to improve energy efficiency of existing buildings by optimal sizing, matching and timing control of facilities in the building. This is however out of the scope of this study and not considered.

The main contributions of this study are stated in the following. Firstly, a systematic approach to determine the optimal retrofit plan for existing buildings considering both the envelope systems and the indoor systems and their interactions to reduce the energy consumption and to ensure compliance with a green building policy with reference to the EPC rating system is presented. The optimal retrofit plan obtained can help a building to achieve a desired energy rating from the EPC rating system in a cost-effective manner. Secondly, factors including energy savings and economic benefits, which are important to decision makers, are built into the proposed optimization model to make sure that the economic benefits of an investment project are maximized and the desired energy savings is achieved. Thirdly, the proposed model treats the retrofit plan as a multi-year project with improving efficiency targets in the consecutive years. That is to say, the model breaks down the one-time long-term project into smaller projects over multiple financial years with shorter payback periods. This is of great help to mitigate the concerns of the investors. In view that obtaining the best rating (grade A) usually requires a significant amount of investment with a long payback period and the high economic uncertainties, breaking the investment down in short-term ones helps to attract investments for similar building retrofit projects. The proposed approach in this study will make sure that at least the so-called 'low-hanging fruits' projects, which generate noticeable savings with a relatively small investment, for energy efficiency improvement will be implemented in the starting years of the retrofit project. Lastly, the government of South Africa, struggling from sever energy supply constraints, has implemented a series of initiatives to promote efficient utilization of the country's limited power generating capacity in recent years. The tax incentive program introduced under the section 12L of the income tax act is one of these initiatives. It allows business owners to claim a deduction of their taxable income according to their energy savings over a year comparing to their baseline consumption in the previous year. The 12L tax incentive program helps to bring in an additional cash flow by means of reduced tax paid by the building owner, which can be used to fund the new retrofit projects in the coming years and can further shorten the payback period of the retrofit project. This tax incentive program is also considered in the optimal retrofit planning method.

Relevance of this research to the building retrofit field can be stated from two aspects. From the application point of view, this study develops a powerful decision support tool for the whole building energy efficiency retrofit aiming at a green building rating taking into account all possible retrofit activities, interactions between the indoor and envelope systems of a building, and financial incentives over several years. From the academic perspective, the presented optimization model adds value to the literature on the green building retrofit by introducing a systematic model capable of optimizing the retrofit actions of both envelope and indoor facilities of a building simultaneously. This systematic approach essentially develops a retrofit planning tool for buildings involving multi-technologies, which was found to be difficult [39]. It also features a multi-year planning architecture that helps to ease the mind of investors and helps to evaluate the financial and energy savings benefits of the retrofit over a realistic multi-year scale [39]. Moreover, the formulated optimal retrofit planning problem is a nonlinear mixed-integer programming (NMIP) problem that cannot be solved by conventional optimization techniques and consequently, a genetic algorithm (GA) is developed in this study to solve this NMIP problem. It should be noted that the focus of this study is developing the optimization model to "identify the most cost-effective retrofit measures for particular projects" and not the optimization algorithm to solve this problem. Although a GA based algorithm is adopted, it should be noted that this problem can be solved by other algorithms as well. Investigation of the most efficient algorithm to solve the formulated problem will be reported in our future works.

The remainder of this paper includes five parts. Modeling of the building energy consumption is presented in Section 2 followed by the optimal retrofit problem formulation in Section 3. After that, a case study covering all aspects of the whole building retrofit problem is given in Section 4 and conclusions are drawn in Section 5.

2. Energy modeling of the building

The energy consumption of the various components of a building must be mathematically modeled before the retrofit problem can be formulated. This section presents the equations that govern the energy usage of a building. Specifically, the heating and cooling energy usages are modeled considering the heat flows through the envelope materials and the characteristics of the heating and cooling facilities. The energy consumption of lighting system and appliances inside the building is then modeled. Lastly, a photovoltaic (PV) system is included in the model to produce electricity for the building in order to help it to reach the desired grade. The motivation of such a PV system is because that South Africa is one of the countries in the world that has the best solar resource, and that other energy saving technologies such as district heating infrastructures are not available in the country. It is however noted that if other energy saving systems are available, they can be modeled and then incorporated in the optimal retrofit plan model developed in this study, which sets a general framework for the optimal retrofit plan with reference to the EPC rating system.

The impacts of the envelope components on the energy consumption of the building are modeled first followed by the energy consumption model of the lighting and appliances. Modeling of the rooftop PV power supply system comes at the end of this section.

In the following subsection, equations for the cooling and heating loads calculation are derived from Refs. [40,41] if not specifically stated otherwise.

2.1. Cooling energy consumption

In a general building, the energy consumption for the cooling load includes the following parts: transmission heat gain, infiltration and ventilation heat gain, solar heat gain, and internal heat gain.

2.1.1. Transmission heat gain

The transmission heat gain of the cooling load in a general building in year t can be determined by

$$E_{tc}(t) = C_{dd}(t)(A_{win}U_{win}(t) + A_{wal}U_{wal}(t) + A_{rof}U_{rof}(t) + A_{flr}U_{flr}(t)) \tag{1}$$

In this study, the floor of the building is not considered to be retrofitted. Hence, the thermal transmittance of the floor $U_{flr}(t)$ keeps unchanged. The thermal transmittances of the other envelope components of the building after the retrofit are calculated by

$$U_{win}(t) = \sum_{i=1}^{I} x_i^{win}(t)U_i, \tag{2}$$

$$U_{wal}(t) = \sum_{j=1}^{J} x_j^{wal}(t)\frac{U_w\lambda_j}{U_w d_j + \lambda_j}, \tag{3}$$

$$U_{rof}(t) = \sum_{k=1}^{K} x_k^{rof}(t)\frac{U_r\lambda_k}{U_r d_k + \lambda_k}, \tag{4}$$

in which $x_i^{win}(t)$ denotes the state of the i-th alternative of the windows, i.e., when $x_i^{win}(t) = 1$, it is chosen to retrofit the existing window in year t, while if $x_i^{win}(t) = 0$, it is not chosen.

2.1.2. Infiltration and ventilation heat gain

The infiltration and ventilation heat gains of the cooling load in a general building consist of sensible and latent components. The sensitive heat gain in year t can be calculated by

$$E_{sc}(t) = C_s Q_s C_{dd}(t). \tag{5}$$

The latent heat gain in year t can be calculated by

$$E_{lc}(t) = C_l Q_s \Delta W(t) T_c(t). \tag{6}$$

2.1.3. Solar heat gain

The solar heat gain of the cooling load in a general building in year t can be calculated by

$$E_{sl}(t) = A_{win}I_{win}(t)SHGC(t)T_s(t). \tag{7}$$

In the calculation of $SHGC(t)$, the shading factor is not considered in this study.

2.1.4. Internal heat gain

The internal heat gain of the cooling load in a general building mainly results from people, lightings and appliances. It can be calculated by

$$E_i(t) = (\alpha_1 + \alpha_2 + \alpha_3)A_g T_{oc}(t). \tag{8}$$

2.1.5. Energy consumption of the cooling load

The cooling loads detailed in Sections from 2.1.1 to 2.1.4 are supplied by chillers installed in the building. The following equation is used to determine the energy consumed by the chillers to supply these cooling loads [42].

$$E_{cool}(t) = \frac{E_{tc}(t) + E_{sc}(t) + E_{lc}(t) + E_{sl}(t) + E_i(t)}{SEER(t)}. \quad (9)$$

SEER is a ratio of the cooling output in BTU over the cooling season to the used watt-hours electricity input during the same period measured in Btu/Wh. When the exiting chiller is retrofitted by a new one, the resulting SEER is determined by

$$SEER(t) = \sum_{c=1}^{C} x_c^{chi}(t) SEER_c. \quad (10)$$

2.2. Heating energy consumption

The heating load for a building includes two parts, namely, transmission heat loss and infiltration and ventilation heat loss.

2.2.1. Transmission heat loss

The transmission heat loss through the envelope in year t is calculated by

$$E_{th}(t) = H_{dd}(t)(A_{win}U_{win}(t) + A_{wal}U_{wal}(t) + A_{rof}U_{rof}(t) + A_{flr}U_{flr}(t)) \quad (11)$$

2.2.2. Infiltration and ventilation heat loss

The infiltration and ventilation heat loss consists of sensitive and latent heat losses. The sensitive heat loss in year t can be calculated by

$$E_{sh}(t) = C_s Q_s H_{dd}(t), \quad (12)$$

and the latent heat gain in year t can be calculated by

$$E_{lh}(t) = C_l Q_s \Delta W(t) T_h(t). \quad (13)$$

2.2.3. Energy consumption of the heating load

The heat loads determined in Sections 2.2.1 and 2.2.2 are supplied by heat pumps in the HVAC system. Accounting for the efficiency of the heat pump, the electrical energy used for the heating purpose can be determined by Ref. [42].

$$E_{heat}(t) = \frac{E_{th}(t) + E_{sh}(t) + E_{lh}(t)}{HSPF(t)}. \quad (14)$$

HSPF is defined as the heating output in BTU during the heating season divided by the total electricity energy input in watt-hours during the same period measured in Btu/Wh. When the heat pump is retrofitted, the resulting HSPF can be calculated by

$$HSPF(t) = \sum_{h=1}^{H} x_h^{pum}(t) HSPF_h. \quad (15)$$

2.3. Lighting and appliance energy consumption

In addition to heating and cooling energy consumption, lighting systems and appliances in the building also consume energy. This part of energy usage in year t is calculated by

$$E_d(t) = (P_l(t) + P_a) T_d(t). \quad (16)$$

2.4. PV system energy production

The energy produced by the PV system in year t depends on the local solar radiation and is calculated by Refs. [43,44]:

$$E_{pv}(t) = I_{pv}(t)\eta_s \sum_{p=1}^{P} x_p^{pv}(t)\eta_p \sum_{p=1}^{P} x_p^{pv}(t) A_p^{pv} \sum_{t=1}^{t} N_{pv}(t). \quad (17)$$

Table 1
Energy performance scale.

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

2.5. Total energy consumption of a building

Summing up all the energy consumption and generation in the building from Section 2.1 to Section 2.4, the total energy consumption of the building during year t can be calculated by

$$E_{tot}(t) = E_{cool}(t) + E_{heat}(t) + E_d(t) - E_{pv}(t). \quad (18)$$

3. The energy-efficiency retrofit problem

The objective of the retrofit is to obtain a desired EPC rating in order to comply with the green building policy. Therefore, the details on the EPC rating system are briefly discussed first.

3.1. EPC for buildings

The EPC rating system assigns a grade from A (most efficient) to G (most inefficient) to a building by comparing its actual net annual energy usage in kilowatt hours per square meter to a reference value set by the national standard SANS10400-XA [6]. To be exact, the requirements to reach different energy performance grades are detailed in Table 1, in which E_r is the reference net annual energy consumption in kilowatt hours per square meter. The value of E_r for a target building is determined by the occupancy type and climate zone of the building which can be found in Ref. [6]. For instance, the value of E_r is set to 190 kWh/m^2 for an office building operating in climate zone 2 while it is set to 630 kWh/m^2 for a hotel operating in climate zone 6.

The minimum requirement for target buildings is to obtain a D rating from the EPC at least. Therefore, the main aim of the presented optimization model in this study is to design an optimal energy efficiency retrofit plan for existing buildings that will ensure compliance with the green building policy and maximize the economic benefits of the retrofit.

As mentioned in Section 1, the one-time long-term investment project is breakdown into yearly investments with shorter payback periods. Keep in mind that tighter regulation may come into effect in the coming years, the targeted rating for each consecutive year can be different. Therefore, the retrofit plan problem can be put in the following optimization problem format.

$$\begin{aligned} &\textbf{max} \quad \text{energy savings} \\ &\textbf{min} \quad \text{payback period} \\ &\textbf{s.t.} \quad \text{desired EPC rating, and} \\ &\qquad\quad \text{budget available} \end{aligned} \quad (19)$$

In this study, the retrofit actions focus on the retrofit of envelope components, including windows, walls, and roof; the replacement of the chiller, heat pump in the HAVC system and the lighting fixtures in the building by more efficient models; and installation of a rooftop PV power supply system to produce electricity for the building. Details of this optimization problem are formulated in the following subsections with the following assumptions:

1) The occupancy type of the building over the planning period remains unchanged, i.e., an office building will continue to serve as an

office building and will not be used for other purposes.
2) Proper maintenance of the retrofitted items is practiced such that the resulting energy savings is persistent.
3) Any existing item will only be retrofitted once during the project period. For instance if the heat pump is retrofitted by a certain alternative in year one, no further retrofit of this alternative will happen during the project period.

3.2. Decision variables

Assume that there are I alternatives of windows, J alternatives of wall insulation materials, K alternatives of roof insulation materials, C alternatives of chillers, H alternatives of heat pumps, and P alternatives of solar panels available for the retrofit. And that, there are m types of existing lightings to be retrofitted and L_m alternatives for retrofitting the m-th type. Let

$$X_{win} = [x_1^{win}(1), ..., x_I^{win}(1), ..., x_1^{win}(T), ..., x_I^{win}(T)]$$
$$X_{wal} = [x_1^{wal}(1), ..., x_J^{wal}(1), ..., x_1^{wal}(T), ..., x_J^{wal}(T)]$$
$$X_{rof} = [x_1^{rof}(1), ..., x_K^{rof}(1), ..., x_1^{rof}(T), ..., x_K^{rof}(T)]$$
$$X_{chi} = [x_1^{chi}(1), ..., x_C^{chi}(1), ..., x_1^{chi}(T), ..., x_C^{chi}(T)]$$
$$X_{pum} = [x_1^{pum}(1), ..., x_H^{pum}(1), ..., x_1^{pum}(T), ..., x_H^{pum}(T)]$$
$$X_{pv} = [x_1^{pv}(1), ..., x_P^{pv}(1), ..., x_1^{pv}(T), ..., x_P^{pv}(T)]$$
$$X_{lig_m} = [x_1^{lig_m}(1), ..., x_{Lm}^{lig_m}(1), ..., x_1^{lig_m}(T), ..., x_{Lm}^{lig_m}(T)]$$
$$N = [N_{pv}(1), ..., N_{pv}(T), N_{lig_1}(1), ..., N_{lig_1}(T), ..., N_{lig_m}(1), ..., N_{lig_m}(T)]$$

The decision variable of the optimization problem is then given by:

$$X = [X_{win}, X_{wal}, X_{rof}, X_{chi}, X_{pum}, X_{pv}, X_{lig_1}, ..., X_{lig_m}, N].$$

3.3. The objective function

As seen in (19), the objectives of the retrofit problem will maximize energy savings and minimize the payback period of the retrofit.

Energy savings resulted from the retrofit is calculated by

$$ES(t) = E_{pre} - E_{tot}(t). \tag{20}$$

Taking into annual discounts of the cash flow, the following formula is used to determine the discounted payback period of the retrofit project [45].

$$T_p = M + \frac{|\overline{C_f}(M)|}{C_f(M+1)}. \tag{21}$$

In the calculation of cash flows of the investment, the tax incentive program is taken into account. The incentive program promotes green development by reducing the amount of total taxable incomes of the owner of the buildings according to the energy savings achieved annually. Therefore, the actual monetary incentive for the building owner is calculated by multiplying the offset amount by the tax rate of the individual/business. It can be obtained by

$$R(t) = (E_{tot}(t-1) - E_{tot}(t))\zeta_a\zeta_t. \tag{22}$$

Combining Eqs. (20) and (22), the discounted cash flows of the retrofit problem can be obtained by

$$C_f(t) = \frac{-C(t) + p(t)ES(t) + R(t)}{(1+d)^t}. \tag{23}$$

The retrofit cost in year t is calculated by

$$C(t) = A_{win}\sum_{i=1}^{I} x_i^{win}(t)C_i^{win} + A_{wal}\sum_{j=1}^{J} x_j^{wal}(t)C_j^{wal} + A_{rof}\sum_{k=1}^{K} x_k^{rof}(t)C_k^{rof} + \sum_{c=1}^{C} x_c^{chi}(t)C_c^{chi} + \sum_{h=1}^{H} x_h^{pum}(t)C_h^{pum} + N_{pv}(t)\sum_{p=1}^{P} x_p^{pv}(t)C_p^{pv} + \sum_{m=1}^{m}\sum_{l_m=1}^{L_m} x_{l_m}^{lig_m}(t)C_{l_m}^{lig_m}N_{lig_m}(t). \tag{24}$$

Eventually, the multiple objective optimization problem that maximizes the energy savings and minimizes the payback period is converted to a single objective optimization problem making use of the weighted sum method [46–48] with the following combined cost function

$$J = -w_1\sum_{t=1}^{T} ES(t) + w_2 T_p. \tag{25}$$

During the optimization process, the values of the two objectives are normalized with respect to their base case for the convenience of tuning the weighting factors in the optimization process.

3.4. The constraints

The constraints of the optimization problem consist of three parts. The first constraint is the limit on the available budget, which is described as

$$C(t) \le \beta_t. \tag{26}$$

The second one is to ensure target buildings to obtain desired EPC ratings. It is described as

$$E_p(t) < \delta(t)E_r, \tag{27}$$

where $\delta(t)$ takes the values from Table 1. For example, $\delta(t) = 1.1$ ensures that the energy performance of the building must reach grade D at least in year t. The energy performance of the building in year t can be described by Ref. [5]:

$$E_p(t) = \frac{E_{tot}(t)}{A_g}. \tag{28}$$

The third kinds of constraints are some physical limits of the retrofit, including the limit on usable area of the roof for PV system installation

$$\sum_{t=1}^{T}\sum_{p=1}^{P} x_p^{pv}(t)A_p^{pv}N_{pv}(t) \le A_e, \tag{29}$$

and boundary limits on the decision variables

$$\begin{cases} \sum_{i=1}^{I} x_i^{win}(t) \in \{0,1\}, i = 1,2,...,I \\ \sum_{j=1}^{J} x_j^{wal}(t) \in \{0,1\}, j = 1,2,...,J \\ \sum_{k=1}^{K} x_k^{rof}(t) \in \{0,1\}, k = 1,2,...,K \\ \sum_{c=1}^{C} x_c^{chi}(t) \in \{0,1\}, c = 1,2,...,C \\ \sum_{h=1}^{H} x_h^{pum}(t) \in \{0,1\}, h = 1,2,...,H \\ \sum_{p=1}^{P} x_p^{pv}(t) \in \{0,1\}, p = 1,2,...,P \\ \sum_{l_m=1}^{L_m} x_{l_m}^{lig_m}(t) \in \{0,1\}, l_m = 1,2,...,L_m. \end{cases} \tag{30}$$

The each of the $x_i^{win}(t)$, $x_j^{wal}(t)$, $x_k^{rof}(t)$, $x_c^{chi}(t)$, $x_h^{pum}(t)$, $x_p^{pv}(t)$, $x_p^{pv}(t)$ and $x_{l_m}^{lig_m}(t)$ takes the value of either zero or one.

4. Case study

To analyze the effectiveness and feasibility of the optimization model, an existing office building situated in Pretoria, South Africa, the Koppen-Geiger climate of which is Cwa, is used as a case study in this section. The building has a gross area of 568 m^2 and consists of two floors with the same structure, which is shown in Fig. 1.

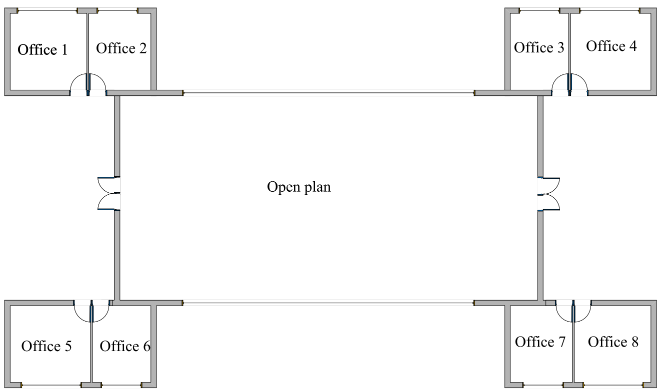

Fig. 1. Floor plan of the office building under study.

Table 2
Alternatives of windows.

i	Alternatives	U_i (W/m°C)	C_i^{win} ($/m^2)
1	Single glazing, aluminum frame	1.25	21.00
2	Double glazing, uncoated air-filled metallic frame	0.82	38.00
3	Double glazing, tinted uncoated air–filled metallic frame	0.49	50.00
4	Double glazing, tinted coated air–filled metallic frame	0.38	80.00
5	Double glazing, low-e window, air-filled metallic frame	0.32	97.00

Table 3
Alternatives of external wall insulation materials.

j	Alternatives	d_j(m)	λ_j(W/m°C)	C_j^{wal}($/m^2)
1	Stone wool	0.03	0.034	14.49
2	Glass wool	0.05	0.038	16.32
3	EPS	0.03	0.036	9.84
4	EPS	0.07	0.036	13.45
5	EPS	0.08	0.036	14.37
6	EPS	0.08	0.033	21.10
7	EPS	0.04	0.036	10.44
8	EPS	0.06	0.036	12.32
9	SPF	0.02	0.042	8.23
10	Cork	0.01	0.040	3.93
11	Cork	0.10	0.040	23.13
12	Cork	0.15	0.040	34.70
13	Cork	0.30	0.040	69.38

The existing windows of the building are single glazing and the existing roof, walls and floor have no thermal insulation. The retrofit plan for this building includes a set of actions. For the envelope, retrofit of the windows using better alternatives is considered and insulation materials are considered to be installed to the walls and roof. The existing lighting system is to be upgraded by more energy efficient models and the chiller and heat pump in HVAC system are to be retrofitted with their more efficient counterparts. Installation of a PV power supply system is also part of the retrofit options. The detailed information of the systems/components used for the retrofit, including windows, wall and roof insulation materials, chiller, heat pump, and PV panels, is given in Tables 2–8. In Table 8, three alternative lighting technologies are listed to retrofit the corresponding existing technologies. The baseline energy consumption of the building before the retrofit is 120.6 MWh per year. The discount rate involved in the optimization process is set at 6% according to South Africa statistics.[1] The rate of

[1] http://www.statssa.gov.za/.

Table 4
Parameters of roof insulation materials.

k	Alternatives	d_k(m)	λ_k(W/m°C)	C_k^{rof}($/m^2)
1	SPF	0.020	0.042	8.23
2	EPS	0.030	0.033	5.57
3	EPS	0.040	0.033	7.22
4	EPS	0.050	0.033	8.85
5	EPS	0.060	0.033	10.49
6	EPS	0.070	0.033	12.15
7	EPS	0.080	0.033	13.79
8	EPS	0.040	0.034	15.00
9	Stone wool	0.065	0.037	31.78
10	Stone wool	0.105	0.037	44.84

Table 5
Parameters of chiller alternatives.

c	Alternatives	SEER	C_h^{pum}($)
1	Trane chiller type 1	17.0	8580
2	Trane chiller type 2	15.0	7590
3	Trane chiller type 3	12.0	6435

Table 6
Parameters of heat pump alternatives.

h	Alternatives	HSPF	C_c^{chi}($)
1	Trane heat pump type 1	9.5	7920
2	Trane heat pump type 2	8.6	7425
3	Trane heat pump type 3	7.9	5775

Table 7
Parameters of solar panels.

l	Alternatives	C_l^{pv}($)	η_l	A_l^{pv}(m^2)
1	STP255-20/WD	900.78	15.7%	1.627
2	YL190P-23B	592.62	14.7%	1.297
3	YL265C-30B	942.30	16.3%	1.624
4	CS6X-300P	870.33	15.6%	1.919
5	HSL60P6-PB-1-240B	704.82	14.8%	1.616
6	Sharp ND 245 Poly	1023.12	14.9%	1.642
7	SW 275 MONO	1042.50	16.4%	1.593

increase in the electricity price in South Africa is determined as 12.69% according to the average increase rate of electricity published by Eskom, which is the largest utility in South Africa.[2] The values of other parameters involved in the optimization model are taken from the national code on the energy efficiency in buildings [49].

For this particular building studied, EPC rating system gives it a E rating before the retrofit. Therefore, to improve the energy efficiency in order to reach D rating for policy compliance and subsequently C, B and A rating in the following years, the retrofit plan considers an implementation period of the retrofit of four years. In particular, the retrofit plan will improve the EPC rating of this building to D in year one and to grade C in year two, and eventually to grade A in year four to first ensure policy compliance and then pursuit better energy efficiency.

In this study, a genetic algorithm (GA) is employed to solve the multi-objective optimization problem [50,51]. With the genetic algorithm, the optimization problem is solved with the weighting factors set to $w1 = 0.7$ and $w2 = 0.3$. The budgets allocated to each year for the

[2] Eskom. Historical average price increase. http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Pages/Tariff_History.aspx. Accessed 7th Dec. 2016.

Table 8
Parameters of lighting technologies.

l_m	Existing lighting	N_{lm}	Alternatives	C_{lm}^{ligm}($)
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	Halogen 50 W − 12 V	56		
			LED flood 7 W	8.5
			LED flood 10 W	12.2
			LED flood 14 W	17.7
l_4	Incandescent 100 W	32		
			LED bulb 12 W	79.5
			LED bulb 17 W	53.0
			LED bulb 20 W	42.4
l_5	Incandescent 60 W	68		
			LED bulb 12 W	79.5
			LED bulb 17 W	53.0
			LED bulb 20 W	42.4

Table 9
The optimal solution.

	Year 1	Year 2	Year 3	Year 4
$\beta(t)$ ($)	2000	7000	30000	70000
$C(t)$ ($)	1425	6991	18959	69742
Window	0	0	0	0
Wall	0	10	0	0
Roof	0	0	0	2
Chiller	0	0	1	0
Heat pump	0	0	1	0
PV	0	0	0	5
N_{pv}	0	0	0	97
L_1	1	3	0	0
N_{lig_1}	75	5	0	0
L_2	0	2	0	0
N_{lig_2}	0	48	0	0
L_3	0	3	0	0
N_{lig_3}	0	56	0	0
L_4	0	2	0	0
N_{lig_4}	0	32	0	0
L_5	0	2	3	0
N_{lig_5}	0	10	58	0
$t_p(t)$ (month)	8	20	44	90
$ES(t)$ (kWh)	12096	34433	58111	93852
$ES_p(t)$	10%	29%	48%	78%
$E_p(t)$	1.01	0.80	0.58	0.25

Table 10
RSD of investment's indicators.

	Payback period	Energy saving	NPV	Energy intensity
RSD	1.72%	1.19%	1.88%	5.12%

building retrofit are $2000, $7000, $30000 and $70000, respectively. The results obtained by the optimization procedure are given in Table 9. In Table 9, the numbers shown in the last four columns from the fourth row onward indicate the retrofit decision on the corresponding items listed in the first column. L_1, L_2, L_3, L_4 and L_5 represent the five existing lighting technologies. N_{pv}, N_{lig_1}, N_{lig_2}, N_{lig_3}, N_{lig_4} and N_{lig_5}, represent the numbers of installed solar panels and the numbers of lamps replaced. For example, the number '10' in the fifth row of the third column means that the tenth alternative of the wall insulation materials will be applied to the walls of the office building under study in the second year. The '1' for L_1 and '75' for N_{lig_1} in the year one means that 75 of the first type of the existing lighting technologies will be replaced by its first alternative shown in Table 8. A '0' in the table indicates that the corresponding item will not be retrofitted in that year. In addition, Table 9 also shows the payback periods of the individual investments made at each year ($t_p(t)$). For instance, in year one, t_p is eight months, which corresponds to the payback period of the $1452 investment. The resulting absolute and percentage energy savings, $ES(t)$ and $ES_p(t)$, together with the energy intensity, $E_p(t)$, are also listed in the table.

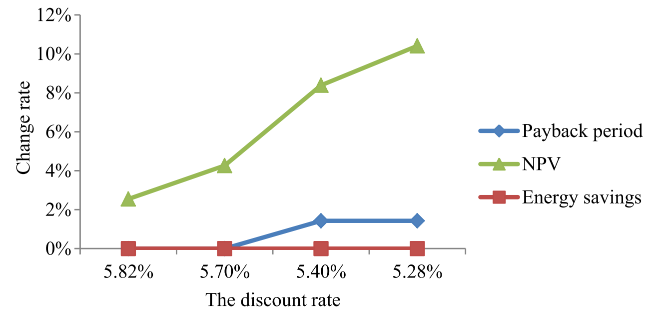

Fig. 2. Sensitivity analysis of the discount rate.

The results obtained indicate that the lighting retrofit is the most cost-effective option followed by retrofit of HVAC facilities. Installation of PV system and retrofitting the envelope of the building require a long payback period. However, it can be concluded from Table 9 that the PV system can generate remarkable energy savings by comparing the values of ES_p in years 3 and 4, which positively contributes to the sustainability and environmental friendliness of the building.

Therefore, the optimization chooses the best combination of retrofit actions for the optimal plan. Table 9 shows that only the first lighting technology is retrofitted in the first year to achieve the desired EPC rating 'D'. Most of the lightings are replaced and the insulation is installed for the walls in the second year. It is noticed that not all of the last lighting technologies are retrofitted in the second year because of target grade 'C' requiring more energy savings, which is satisfied by the wall insulation. To reach grade 'B' rating in year three, the remaining quantities of the fifth lighting technology is retrofitted and the HVAC facilities are upgraded. The roof and solar panels are lastly considered in the forth year.

Intuitively, the payback period of the lighting system is the shortest while that of the envelope is the longest. Without help of the proposed optimization model, the decision maker is limited to this intuition and can only make retrofit plans accordingly, which, as demonstrated by the optimization result, will result in non-optimal retrofit activities. This demonstrates the effectiveness as well as the importance of the proposed optimal retrofit plan model.

The cumulative energy savings and net present value over ten-year period, and payback period of the total investment are given in Fig. 3. It is shown that the optimal retrofit plan results in 761.6 MWh energy savings, a net present value of $81003 with a payback period of 70 months.

Since GA is adopted to solve the optimization problem formulated, a statistical analysis of the results obtained is done through 20 run of the simulations. The relative standard deviations of the cumulative energy savings, net present value and the payback period of the building retrofit project and the energy intensity of the building are presented in Table 10, which are 1.19%, 1.88%, 1.72% and 5.12%, respectively. The results verify the effectiveness and convergence of the solution obtained by the GA algorithm.

As the parameters considered in the optimization process influence the optimal results, this study analyzes the effects of the discount rate, weighting factors and tax incentive on the proposed model.

Firstly, the discount rates with values of 5.82%, 5.70%, 5.40% and 5.28% are introduced. The resulting changes in the investment

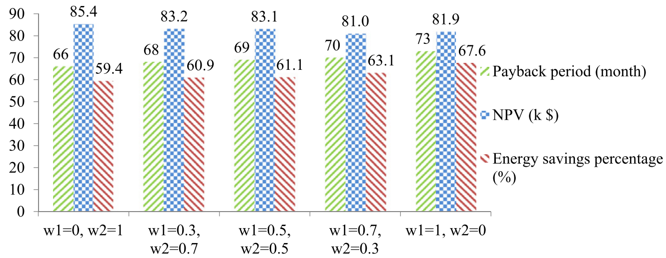

Fig. 3. Optimal retrofit plans with different weighting factors.

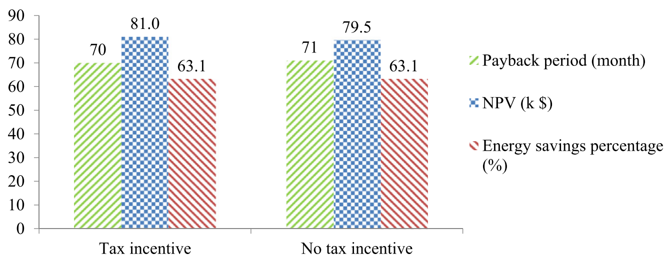

Fig. 4. Comparison between retrofit plans with and without tax allowance, $w_1 = 0.7.w_2 = 0.3$

indicators of applying the new discount rates are detailed in Fig. 2. To be specific, the optimal solution to the whole-building retrofit problem remained the same, thus leading to no change in the energy savings obtained. However, the payback period and NPV of the project change when the discount rate varies. It can be concluded from Fig. 2 that the energy savings are robust against the uncertainty on the discount rate while the economic factors are sensitive to its change. For instance, the NPV grows by 10.41% and the payback period decreases by 1.43% when the discount rate decreases to 5.28%."

Four more sets of results with the weighting factors in the objective function (25) set to different values are presented in Fig. 2. It can be seen that a shorter payback period and more energy savings can be achieved when the values of their corresponding weighting factors grow. For instance, the payback period of the project increases by 2.9% (from 68 to 70 months) and the percentage of energy savings increases by 3.6% (from 60.9% to 63.1%) when the values of the weighting factor change from $w1 = 0.3$ and $w2 = 0.7$ to $w1 = 0.7$ and $w2 = 0.3$. Comparing the five sets of results with different weighting factors, one can find that the shortest payback period of the retrofit can be obtained when the decision makers emphasizes minimization of the payback period with $w1 = 0$ and $w2 = 1$ and the most energy savings can be achieved when emphasis is put on the energy savings with $w1 = 1$ and $w2 = 0$.

Lastly, the optimization problem with $w_1 = 0.7$ and $w_2 = 0.3$ is solved again without taking into account the tax incentive program in view that some of the government owned buildings do not qualify for tax allowance. The ten-year energy savings and economic indicators obtained are shown in Fig. 4. It can be seen that the payback period is longer and the net present value is less than the case when the tax incentive is considered (see Fig. 3). However, it is seen that the tax incentive program has very limited impact on the building energy efficiency retrofit. To be exact, the payback period increased marginally by one month (1.4%) and the net present value decreased slightly by 1.5 thousand dollars (1.9%).

5. Conclusion

The focus of this paper is to develop a systematic optimization method for whole-building retrofit planning, aiming at reducing the energy consumption of existing buildings for green building policy compliance in a cost-effective manner. The main conclusions are given as follows:

- The model developed is able to identify the best retrofit plans for whole-building retrofit projects, taking into account both the envelope components and the indoor appliances. In this study, the retrofit actions considered include upgrade of lighting systems, HVAC facilities, installation of insulation materials to the walls and roof of the building, replacement of windows by more energy-efficient alternatives and installation of a roof top solar power system.
- The optimal retrofit plans obtained by the model can help target buildings to achieve a desired energy rating from the energy performance certificate (EPC) standard set by the South Africa government in the most profitable way.
- The proposed model is capable of breaking down the long-term building retrofit project requiring substantial investment into smaller projects over multiple financial years. This helps decision makers to select the best retrofit activities on a yearly basis to ensure that the energy performance of the building is improved and complies with the green building policy. In such a way, the most energy savings is obtained with a reasonable payback period of the investment.
- The tax incentive program available in South Africa is taken into account by the retrofit planning model to further shorten the payback period of the investment. It is however found that the tax incentive program has little impact on the building energy efficiency retrofit project.

The results of a case study show that 761.6 MWh energy savings and $81003 cost savings can be achieved in 70 months after applying the optimal retrofit plan, which validate the effectiveness and the importance of the model for decision makers because intuitive plans will lead to non-optimal retrofit actions.

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