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An optimal model for a building retrofit with LEED standard as reference protocol

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ABSTRACT

The selection of facilities to be replaced during a building retrofit can be challenging due to conflicting interests such as budget constraints, building minimum requirements, human comfort, and environmental goals. In order to assist decision-makers with the appropriate selection of facilities, this paper presents a multi-objective optimization model aiming at optimizing the retrofitting costs, energy savings, water savings, payback period, and points earned under the Leadership in Energy and Environmental Design (LEED) rating system. This work introduces green building certification as an objective for existing building retrofits. The benefits of an existing building retrofit and green building certification to the building owner includes reduced operating costs, carbon footprint, and improved air quality. The developed model considers a wide range of facilities and saving measures as retrofitting options for the energy and water efficiency credit categories of LEED. A case study of a hotel in South Africa is presented to demonstrate the feasibility of the proposed model and optimization approach.

1. Introduction

The building sector consumes 30–40% of energy and 12% portable water globally [1]. In addition, the reported negative impacts of buildings on the environment result in 45–65% of solid waste and 40% of carbon dioxide emissions [2]. The replacement rate of existing buildings with new buildings is about 1–3% per year [3], resulting in existing buildings being the largest segment of the building sector where energy and water saving opportunities can be identified [4]. Coupled with the global energy crisis and tighter environmental regulations on emissions, reducing the energy consumption of existing buildings is an urgent task. To this end, energy efficiency retrofit is a fast and cost-effective intervention to reduce the energy consumption of existing buildings. Other benefits resulting from this intervention include reduced operating costs, occupant comfort, and reduced negative environmental impacts [5,6].

Governments and private organizations have provided financial assistance towards retrofitting projects. However, there are a number of limitations to the successful implementation of such projects. In particular, building owners and managers are often faced with the challenge of choosing the optimal retrofit measures due to the building's minimum operational requirements, available budget, effectiveness and reliability of the retrofit measures, the uncertainty of economic and environmental benefits as well as the interdependence between the sub-systems of a building [7]. In South Africa, a country facing server energy crisis, the Green Building Council of South Africa predicts an increase in refurbishments of existing buildings because of the high percentage of existing buildings which do not comply with the environmental sustainability standards.[1] Consequently, South Africa has become one of the fastest growing green building markets in the world.[2] To facilitate the transformation of existing buildings to green ones, green building rating systems are introduced. The Leadership in Energy and Environmental Design (LEED) rating system is chosen as the reference green building rating system for this study because it is applicable to different project types and can be adopted globally. The LEED projects completed in South Africa include MTN's head office in Johannesburg, Menlyn Maine in Pretoria and Hotel Verde in Cape Town.

The main focus of this study is therefore to develop a mathematical model that can be used to find the optimal retrofitting actions of an existing building to maximize energy savings and economic benefits while at the same time obtain green building certification.

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[1] South Africa's strong case for green retrofitting http://www.moneyweb.co.za.
[2] Addressing South Africa's energy crisis with a long-term solution http://www.securitysa.com/50731n.

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Nomenclature

n	total number of saving facilities
m	total number of saving measures
x_i^t	quantity of the selected type i facilities to be retrofitted in year t
y_j^t	saving measure type j implemented in year t
X	the decision variable
T	project period
c_i^t	cost of facility i during year t
d_j^t	cost of measure j during year t
es_i	percentage energy savings of facility i
ems_j	percentage energy savings of measure j
ws_i	percentage water savings of facility i
wms_j	percentage water savings of measure j
ec^t	energy cost in year t
wc^t	water cost in year t
ES^t	percentage energy savings in year t
WS^t	percentage water savings in year t
P_E^t	threshold LEED points from energy savings
P_W^t	threshold LEED points from water savings
P_j	check-off LEED points
F_2^0	LEED points obtained from other categories
BEC	building baseline energy consumption
BWC	building baseline water consumption
DPP	discounted payback period
DCF	discounted cash flow
CF_{in}^t	cash inflow in year t
CF_{out}^t	cash outflow in year t
CF^t	net cash flow in year t
d	discount rate t
$CDCF$	cumulative discounted cash flow
t^-	the last period t with a negative cumulative discounted cash flow
z_i	maximum quantity of each type of facility
β_t	budget in US dollar for year t
ρ_t	LEED point target for year t
NPV	net present value at the end of the project
w_1	weighting factor
w_2	weighting factor
w_3	weighting factor

To help a decision maker (DM) to make an optimal retrofit investment plan considering the challenges and conflicting interests, multi-objective optimization models (MOO) and green building rating systems have been introduced [8]. Similarly, other decision aid approaches such as multi-criteria analysis [9] and cost-benefit analysis [10–14] have also been used. When considering MOO for building retrofits, a number of models have been developed to assist with the selection of retrofitting facilities. For instance, a model developed for the selection of technology choices regarding windows, wall insulation, roof insulation, and solar collector types was discussed in [15]. The aim of the model was to simultaneously minimize costs and maximize energy savings, through the assessment of alternatives for each retrofit action. A third objective, maximizing thermal comfort was introduced in [16].

When considering MOO in particular for energy efficiency measures and actions, models developed for the selection of available alternatives in order to maximize energy savings were presented in [17–20]. The results of [17] show the feasibility and benefits of applying multi-objective optimization techniques to energy efficiency improvement retrofits. Consequently, it has become common for DMs to use simulation-based techniques. However, since the aim of these techniques is to overcome the model constraints, the DM is limited to a range of options [19]. In contrast to this, a model presented in [18] was developed and applied through the compromise programming technique. This technique considers an infinite number of alternatives available and has proven its applicability to energy efficient retrofits [18]. To further assist with the optimal selection of available alternatives, building energy simulation methods are used. Results of these optimization methods highlight the importance of assessing any proposed retrofit solution prior to implementing the project [21]. In spite of energy simulation methods, green building rating systems such as LEED were used as the reference when selecting retrofitting measures [22–24]. By using green building rating systems during the selection of retrofit actions, environmental sustainability standards are met and green building certification can be obtained. In [22,25], a model was presented for the selection of building materials (roofs, carpets, paint, glass and wood). The model aims to maximize the points obtained under LEED. The results show that the points achieved are affected by the budget and the design constraints.

Apart from selecting retrofit actions that will result in maximum energy savings and minimum costs, successful retrofit solutions must also relate to minimizing their negative impacts on the environment. As a result, MOO models have been developed to minimize environmental impacts [26,27]. On many occasions, building owners and managers are hesitant to participate in building retrofitting projects due to economic uncertainty. Building stakeholder will be more willing to participate once the financial benefits are known. Consequently, to assist in this regard and make retrofitting projects more attractive, optimization models specifically designed for the financial benefits of retrofitting projects have been developed. The model presented in [28] aimed to maximize energy savings and minimize the payback period simultaneously.

With reference to the aforementioned research, a number of MOO models have been developed to assist the DM when selecting facilities for an existing building retrofit. Some of the reported studies considered the LEED rating system [29,22] but the problem formulated cannot obtain green building certification. Moreover, not all the LEED point categories were considered. For instance, a model aimed to maximize the awarded threshold points for material selection of a carpet system was reported in [25]. However, check-off points were not considered. With respect to the economic viability analysis of retrofitting projects, simple payback period was used in existing studies [28,30], which ignored the important aspect, time value of money, of an investment.

This research introduces a MOO model for the selection of retrofit measures in an existing building. The main contribution of this work is that the model is developed by using the LEED green building standards as a reference. Furthermore, this work introduces green building certification as an objective for existing building retrofits. This has not been done in previous models for existing building retrofits. In order to maximize the points required for LEED certification, retrofitting facilities and measures are identified for the energy and water efficiency categories. These categories contribute up to 50% of the available points. The limitation of available funds is also considered by implementing the retrofitting project over several years, thus enabling the DM to reinvest savings from the preceding years and reduce initial investment. Consequently, the time value of money is considered by applying the discounted payback period (DPP).

A mathematical formulation of the model and the corresponding results are presented. The model developed is a mixed integer nonlinear programming (MINLP) problem, and the open source mixed integer (BONMIN) optimization tool[3] is used to solve the problem. The optimization results show the optimal number of selected facilities and measures that result in the minimum retrofitting costs, maximum LEED points and the minimum DPP.

The remainder of this paper consists of 5 sections categorized as follows: Section 2 describes the LEED for Existing Buildings (LEED-EB)[4] credit categories considered for this study. Section 3 presents the formulation of the multi-objective optimization model. Section 4 presents a case study of a building in South Africa, description of the data used and analysis of the results obtained. Section 5 concludes the paper and proposes future research.

2. LEED-EB credit categories for energy and water efficiency retrofits

LEED is a rating system developed by the U.S. Green Building Council (USGBC). The intended purpose of LEED is to assist building owners and managers when identifying and implementing measures for green building projects [31]. Though various green building certification programs have been developed over the years, the LEED certification program has gained popularity and is used globally due to its reliability, applicability to multiple project types, and its point system, which necessitates earning of points across a range of categories, thus enabling a more holistic approach to prioritizing long-term energy efficiency [32,33].

The LEED-EB rating system provides green building certification through the ranking of points across 5 environmental credit categories. These credit categories are: Sustainable Sites, Water Efficiency (WE), Energy Atmosphere (EA), Materials & Resources, and Indoor Environmental Quality. A maximum of 100 points are available from these categories with an additional 10 points for the Innovation in Operations and Regional Priority credit categories. In order for a project to qualify for LEED certification, all prerequisites must be met and a minimum of 40 points must be obtained. A building can achieve one of four possible certification levels: Certified (obtain 40–49 points); Silver (obtain 50–59 points); Gold (obtain 60–79 points); and Platinum (obtain 80 or more points).[5]

The credit categories considered for this study are WE and EA based on the energy and water saving measures. These categories contribute up to 50% of the 100 base points available, creating a great opportunity for savings and hence green building certification. The assigned points to these credit categories are either threshold or check-off points. The threshold points are earned based on the percentage energy and water savings. For the WE credits, threshold points are awarded based on the percentage water savings as a result of efficient, low-flow and sensor-operated plumbing fixtures, fittings and water systems. Whereas the EA threshold points are awarded based on the percentage energy savings due to energy efficient facilities, renewable energy systems and control systems, the check-off points for both the water and energy categories are awarded based on the building's water and energy consumption, the regular commissioning of systems, the recycling of building material, and the reporting of carbon dioxide emission.

3. The multi-objective optimization model

This section presents the proposed multi-objective optimization model. The decision variables, objective functions, constraints and the optimization technique involved in the problem are thus defined. Assumptions made in formulating the problem are:

- retrofit is done at the beginning of each year;
- savings achieved by the retrofit is persistent over the project period;
- all the LEED prerequisites are met and points are allocated based on the percentage energy and water savings incurred, as well as the measures undertaken;
- the points allocated are based on LEDD-EB; and
- the same LEED version is applicable over the whole project period.

With reference to the second assumption above, maintenance actions can be planned to keep the savings persistent. This is however not the scope of this study. Interested readers can refer to the optimal maintenance plan methods presented in [34–38].

3.1. The decision variables

The decision variables of this problem include alternatives for energy and water savings within an existing building, not resulting in major renovation or reconstruction of the building. For maximum savings, the model considers decision variables in the following two main categories of LEED: threshold points and check-off points. The first category concerns retrofitting of the building's equipment and fixtures consuming energy and water. This includes facilities such as HVAC systems, lighting fixtures, water heaters, and plumbing fixtures. The second category concerns usage of energy and water saving measures such as control systems, meters (to monitor energy and water consumption), and renewable energy and water systems [26]. The retrofitting project is considered to be implemented over several years. This will allow the DM to make the best use of the available funds. The overall energy and water savings are the savings achieved at the end of the last year of retrofit. The cost benefit is the profit obtained as a result of the energy and water savings.

For a retrofitting project over $t = 1, 2, \ldots, T$ years, assume there are n energy and water consuming facilities and fixtures to be retrofitted and m energy and water saving measures to be implemented, the decision variables can be written in a vector X defined by:

$$X = \left[x_1^1, x_1^2, \ldots, x_1^T, x_2^1, x_2^2, \ldots, x_2^T, \ldots, x_n^1, x_n^2, \ldots, x_n^T, y_1^1, y_1^2, \ldots, y_1^T, \ldots, y_m^1, y_m^2, \ldots, y_m^T\right]^T, \tag{1}$$

where x_i^t and y_j^t are the quantity of type i facility to be retrofitted during each year t and the energy or water saving measure j to be implemented during each year t. y_j^t is a binary variable that either takes on the value of 1 or 0, corresponding to whether or not a saving measure is implemented. For simplicity, only one technology is considered for each type of facility or measure. The cost of each facility increases yearly depending on the yearly interest rate.

3.2. Objective functions

The objectives of the optimization model are to minimize retrofitting costs, to maximize LEED points, and to minimize DPP. Mathematical representations of these three objectives are provided in the subsequent contents.

[3] BONMIN 1.8.3 Users Manual.
[4] LEED v4 for Operations & Maintenance: Existing Buildings.
[5] http://new.usgbc.org/leed.

3.2.1. Retrofitting cost

The total investment cost for the existing building retrofit, $F_1(X)$, is calculated by summing the individual retrofit action or saving measure costs over the project period:

$$F_1(X) = \sum_{t=1}^{T}\left(\sum_{i=1}^{n} x_i^t c_i^t + \sum_{j=1}^{m} y_j^t d_j^t\right). \quad (2)$$

3.2.2. LEED points

In order to qualify for LEED certification, all prerequisites must be met, and a minimum of 40 points must be obtained. Assume the baseline energy and water consumption, (BEC) and (BWC), of the building remain constant throughout the project period (i.e. no baseline adjustments are envisaged) [39], the yearly percentage energy and water savings incurred from the retrofit are calculated as follows:

$$ES^t = \frac{\sum_{k=1}^{t}\left(\sum_{i=1}^{n} x_i^k es_i + \sum_{j=1}^{m} y_j^k ems_j\right)}{BEC}, \quad (3)$$

$$WS^t = \frac{\sum_{k=1}^{t}\left(\sum_{i=1}^{n} x_i^k ws_i + \sum_{j=1}^{m} y_j^k wms_j\right)}{BWC}. \quad (4)$$

The threshold points P_E^t and P_W^t are obtained from the energy and water savings, and are defined as:

$$P_E^t = \begin{cases} 0, & \text{if } ES^t < 0.26; \\ 1, & \text{if } 0.26 \le ES^t < 0.27; \\ 2, & \text{if } 0.27 \le ES^t < 0.28; \\ \vdots & \\ 20, & \text{if } 0.45 \le ES^t; \end{cases}$$

and

$$P_W^t = \begin{cases} 0, & \text{if } WS^t < 0.1; \\ 1, & \text{if } 0.1 \le WS^t < 0.15; \\ 2, & \text{if } 0.15 \le WS^t < 0.20; \\ \vdots & \\ 5, & \text{if } 0.3 \le WS^t. \end{cases}$$

The total points for the building retrofit $F_2(X)$, is calculated by adding the points earned by retrofitting energy and water saving facilities, and implementing saving measures as follows:

$$F_2(X) = F_2^0 + P_E^t + P_W^t + \sum_{j=1}^{m} y_j^t P_j, \quad (5)$$

where F_2^0 denotes the points obtained in the other LEED credit categories, and $\sum_{j=1}^{m} y_j^t P_j$ denotes the check-off points obtained by implementing saving measures in year t.

3.2.3. Payback period

The building retrofitting project is implemented over several years, therefore the time value of money has to be considered by applying the DPP. Unlike the simple payback period, the DPP calculates payback period of the investment taking into account time value of money. The DPP is calculated as [40]:

$$F_3(X) = DPP = t^- + \frac{|CDCF_-^t|}{DCF^{t+1}} \quad (6)$$

where t^- is an integer corresponding to the last period t with a negative cumulative discounted cash flow ($CDCF$), $|CDCF_-^t|$ is the absolute value of the $CDCF$ at the end of t^- and DCF^{t+1} is the discounted cash flow (DCF) during the period after t^-. The variables in Eq. (6) are defined as follows.

$$CF_{in}^t = \sum_{i=1}^{n} x_i^t (es_i^t ec^t + ws_i^t wc^t) + \sum_{j=1}^{m} y_j^t (ems_j^t ec^t + wms_j^t wc^t), \quad (7)$$

$$CF_{out}^t = \sum_{i=1}^{n} x_i^t \cdot c_i^t + \sum_{j=1}^{m} y_j^t \cdot d_j^t, \quad (8)$$

$$CF^t = CF_{in}^t - CF_{out}^t, \quad (9)$$

$$DCF^t = \frac{CF^t}{(1+d)^t}, \quad (10)$$

$$CDCF^t = CDCF^{t-1} + DCF^t, \quad (11)$$

where Eqs. (7) and (8) define the cash inflow and outflow at year t. The total DCF in year t is shown in Eq. (10), where d is the discount rate. The CDCF is shown in Eq. (11).

3.3. Constraints

For the practicality of the model, the DM must know what can be feasibly achieved by defining constraints. This results in the feasibility space, on which the decision can be made, and thus assist the DM in obtaining the practical optimal solution. The retrofitting project is completed over several years and the model constraints are implemented yearly. In particular, the constraints of the retrofit optimization problem are:

$$\sum_{t=1}^{T} x_i^t \le z_i, \quad (12)$$

$$y_j^t \in \{1, 0\} \quad \forall \; j = 1, 2, \ldots, m \quad \text{and} \quad t = 1, 2, \ldots, T, \quad (13)$$

$$\sum_{i=1}^{n} x_i^t c_i^t + \sum_{j=1}^{m} y_j^t d_j^t \le \beta_t, \quad (14)$$

$$F_2^0 + P_E^t + P_W^t + \sum_{j=1}^{m} y_j^t P_j \ge \rho_t, \quad (15)$$

$$NPV = CF^0 + \sum_{t=1}^{T} \frac{CF^t}{(1+d)^t} \ge 0. \quad (16)$$

The decision variable constraints are defined in (12) and (13). Inequality (14) defines the retrofit project budget constraint. There are four different certification levels under LEED, for which a minimum number of points is required. The model aims to achieve a higher certification level during each consecutive year, this is defined as a constraint in (15). The constraint in (16) is applied to ensure that the NPV is always positive.

3.4. Solving the optimization model

The optimization model formulated is a multi-objective MINLP problem for the optimal selection of retrofitting facilities and measures. Due to the nature of the problem, the objective functions

Table 1
Hotel annual electricity and water consumption, utility rates, and discount rate.

Building performance indicator	Rate
Annual energy consumption (*BEC*)	22,409,66 kWh
Average electricity billing rate	0.13 $/kWh
Annual water consumption (*BWC*)	60,534 kl
Average water billing rate	1.48 $/kl
Annual energy service charge	$1634.03
Annual energy price increase	12.69%
Annual water price increase	11–17%
Discount rate	9%
Interest rate	7%

described in Section 3.2 are conflicting. Hence to ensure that the model constraints are satisfied and that the conflicting objectives are optimized simultaneously, the weighted sum method is applied to transform the original problem into a single objective optimization problem [41,42]. With the objective functions defined, the aggregated objective function obtained using the weighted sum method is:

$$J = w_1F_1(X) - w_2F_2(X) + w_3F_3(X). \tag{17}$$

The formulated MINLP problem can be solved by optimization solvers such as SCIP and CPLEX etc. In this study, the basic open-source solver, BONMIN's branch-and-bound algorithm, is used due to its properties and solution convergence time [43,44].

4. Case study

4.1. Building description

To demonstrate the applicability of the developed MOO problem, an existing building is analyzed and used as a case study. The building under study is a hotel, located in Pretoria, South Africa. A hotel building is selected as a case study for the following reasons: hotels have different function areas and facilities; hotels operate for an entire day, and have a high occupancy rate, continuous heating or cooling demands are thus required for 24 h. Consequently, hotel buildings generally consume more energy and water when compared to other types of public buildings [45].

The city has a humid subtropical climate, and the average annual temperature is 18.7 °C. The hotel was built in 1987, and its last renovation was in 2014. The building consists of 15 floors and operates 24 h a day throughout the week. The average occupancy rate of the building is 60% as per the South African tourist accommodation statistics. The hotel's main source of energy is electricity supplied by the local municipality. The building's energy charge is based on the time-of-use tariff, and the building has no renewable energy systems installed. For the hotel's hot water supply, four heat pumps of 8.7 kW each are installed. The laundry equipment, HVAC, lighting and water heating systems are the main contributors of energy consumption as shown in Fig. 1. The main contributors of water consumption are the laundry equipment, kitchen, toilets, and showers. There are occupancy controls in two storerooms which switch on/off the lights to save energy. These are the only controls installed in the building. Table 1 shows the energy and water consumption and utility rates as well as the discount rate and interest rate for economic analysis.

4.2. Data collection

A site visit was conducted and an energy audit was done. The existing facilities and measures, as well as the proposed alternatives were identified. These findings are shown in Tables 2 and 3. From these two tables, the number of facility types and saving measures considered for retrofitting are $n = 28$ and $m = 13$ respectively, the retrofitting project is implemented over a period of $T = 4$ years. The maximum quantity of each facility type z_i is based on the number of existing facilities in the hotel. The number of facilities to be retrofitted can thus not exceed this maximum quantity. The unit energy savings (ES) in kWh and water savings (WS) in kl are the average yearly savings achieved from retrofitting facility type $i = 1, 2, \ldots, n$. Furthermore, the per unit energy (ES) and water savings (WS) for each facility type are first calculated based on the number of operating hours, and water consumption a day. For example, the lighting fixtures (facility types $i = 1, 2, \ldots, 17$), are on between 2.5 and 5 h a day. The per unit cost for facility type i (c_i^1) and saving measure j (d_j^1) in USD ($), is the cost of buying the proposed alternative or implementing the proposed saving measure during the first year of the retrofitting project. These prices increase yearly for the following years as a result of the 7% yearly interest rate.

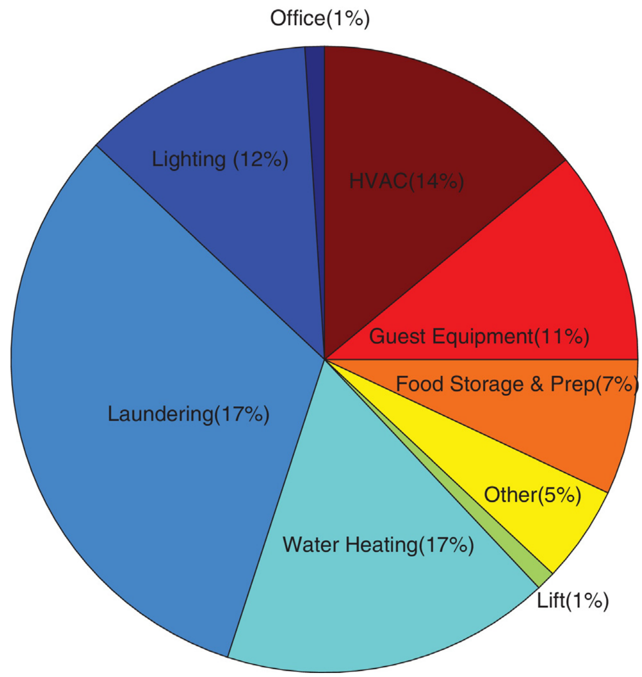

Fig. 1. Hotel energy consumption breakdown.

4.3. Results and discussion

The yearly retrofitting budget allocated to each year t, is strictly for retrofitting purposes, other costs such as labor and the building's energy and water service charge are not included. The LEED points for the other LEED categories (F_2^0) were obtained from the USGBC directory.[6] These points remain constant throughout the project period T. The yearly LEED point target (ρ_t) is based on the different green building certification levels: Certification (obtain 40–49 points); Silver (obtain 50–59 points); Gold (obtain 60–79 points); and Platinum (obtain equal or more than 80 points). The platinum certification level is not considered for this project since it is mainly applicable to LEED projects involving the new construction of buildings. Therefore, $[\beta_1, \beta_2, \beta_3, \beta_4] = [\$15k, \$45k, \$80k, \$350k]$; $F_2^0 = 45$; and $[\rho_1, \rho_2, \rho_3, \rho_4] = [40, 50, 60, 60]$ are used in calculations.

As an illustrative example, Table 4 is presented to demonstrate the solution obtained by the optimization model. In this case, the highest weight is assigned to the retrofitting cost. Therefore the retrofitting cost is minimized as much as possible. The detailed

[6] http://www.usgbc.org/projects/existing-buildings.

Table 2
Building retrofit input data for facilities.

i	Existing facility	Proposed alternative	z_i	Unit ES (kWh/year)	Unit WS (kl/year)	Unit cost c_i^1 ($)
1	Incandescent 40 W	LED bulb 6 W (E27)	78	42	0	10
2	2-lamp 4′ T8 fixture 36 W	2-lamp 4′ T5 28 W	35	30	0	19
3	2-lamp 2′ T8 fixture 18 W	2-lamp 2′ T5 14 W	77	15	0	19
4	1-lamp 4′ T8 fixture 36 W	1-lamp 4′ T5 28 W	54	15	0	19
5	3-lamp 5′ T8 fixture 58 W	3-lamp 5′ T5 35 W	43	63	0	29
6	1-lamp 5′ T8 fixture 58 W	1-lamp 5′ T5 35 W	88	42	0	22
7	PAR 38–65 W	CFL lamp 14 W	112	93	0	35
8	3-lamp 4′ T8 fixture 36 W	3-lamp 4′ T5 28 W	25	44	0	81
9	3-lamp 4′ T8 fixture 36 W	3-lamp 4′ T5 28 W	17	44	0	27
10	2-lamp 5′ T8 fixture 58 W	2-lamp 5′ T5 35 W	23	84	0	22
11	PAR 30–35 W	CFL lamp 7 W	32	57	0	16
12	1-lamp 2′ T8 fixture 18 W	1-lamp 2′ T5 14 W	39	17	0	105
13	Incandescent 250 W	LED bulb 12 W	11	232	0	98
14	4-lamp 4′ T8 fixture 36 W	4-lamp 4′ T5 28 W	29	58	0	20
15	125 W mercury vapor	LED flood 10 W	42	105	0	8
16	Halogen 50 W–12 V	LED 7 W 12 V	42	78	0	8
17	Incandescent 60 W	LED bulb 10 W	41	91	0	117
18	No motion activated lighting (MAL)	(MAL) systems	3	5800	0	1137
19	No sensors	Motion sensors	62	1141	0	255
20	Existing dishwasher	New dishwasher	3	1577	14	849
21	High flow showerheads	Low-flow showerheads	230	1203	11	15
22	Existing washing machines	Energy saving washing machines	25	16422	206	5499
23	Existing dryers	Energy efficient dryers	3	38325	1874	3276
24	Existing ironing machines	Energy efficient ironing machine	3	64260	0	4524
25	Pool pump	Eco pump	15	1569	0	869
26	Existing vending machine	Energy saving vending machine	2	5782	0	3600
27	Old chillers	New chillers	2	25392	0	147125
28	Existing aerators	Aerator upgrade	16	0	904	66

Table 3
Building retrofit input data for saving measures.

j	Existing measure	Proposed alternative	Unit ES (kWh/year)	Unit WS (kl/year)	Unit cost d_j^1($)
1	Poor power factor	Power factor correction	33855	0	55000
2	No photovoltaic systems	Grid connected photovoltaic system	15275	0	54000
3	Existing HVAC system	More efficient HVAC	19800	0	19870
4	No Solar water heater system	Roof mount solar water heater	12700	0	1644
5	No thermal pane glass	Double pane glass for building entrance	8850	0	60900
6	No irrigation system	Drip irrigation system	0	10450	234
7	Existing toilets	Toilets replacement	0	4193	6809
8	Existing faucets	Faucets replacement	0	1061	4488
9	Existing urinals	Urinals replacement	0	2496	5054
10	No building energy meter	Building energy meter	0	0	680
11	No energy sub-system meter	Energy sub-system meter	0	0	680
12	No building water meter	Building water meter	0	0	680
13	No building water sub-system meter	Water sub-system	0	0	680

Table 4
Building performance and economic indicators ($w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$).

	Year 1	Year 2	Year 3	Year 4	Total
Budget ($)	15k	45k	80k	350k	490k
Cost ($)	13k	45k	80k	0k	138k
Energy savings (%)	19	31	41	41	41
Water savings (%)	21	55	59	59	59
Cost benefit ($)	72k	143k	176k	176k	176k
LEED points	48	57	67	67	67

solution of the optimization model is depicted by Tables 5 and 6. Table 4 shows a summary of the results in terms of the building's energy and water savings, LEED points obtained and the investment for the overall retrofitting period. In specific, 28% of the allocated budget was utilized for the overall project. In addition, the maximum available funds for the second and third year were utilized fully. The remaining funds from the first and fourth year may be used to retrofit facilities which were not selected by the model. The accumulative percentage of energy savings incurred by the end of the project is 41%, and the percentage water savings incurred is 59%. In particular, the building's yearly energy and water savings are shown in Fig. 2 where it is evident that the percentage energy and

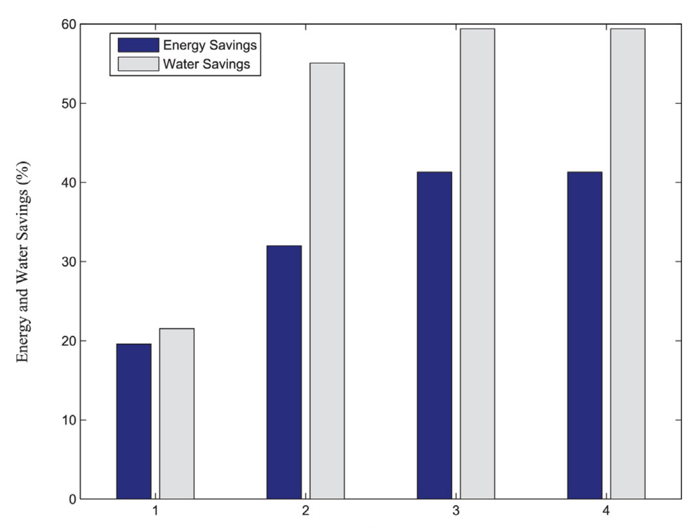

Fig. 2. Energy and water savings ($w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$).

Table 5
Yearly selected facilities ($w_1 = 0.7$, $w_2 = 0.2$, $w_3 = 0.1$).

i	Existing facility	Proposed alternative	z_i	x_i^1	x_i^2	x_i^3	x_i^4	Remaining
1	Incandescent 40 W	LED Bulb 6 W (Candle dimmable) E27	78	0	78	0	0	0
2	2-lamp 4′ T8 fixture 36 W	2-lamp 4′ T5 28 W	35	0	0	0	0	35
3	2-lamp 2′ T8 fixture 18 W	2-lamp 2′ T5 14 W	77	0	0	0	0	77
4	1-lamp 4′ T8 fixture 36 W	1-lamp 4′ T5 28 W	54	0	0	0	0	54
5	3-lamp 5′ T8 fixture 58 W	3-lamp 5′ T5 35 W	43	0	0	0	0	43
6	1-lamp 5′ T8 fixture 58 W	1-lamp 5′ T5 35 W	88	0	0	0	0	88
7	PAR 38–65 W	CFL lamp 14 W	112	0	0	0	0	112
8	3-lamp 4′ T8 fixture 36 W	3-lamp 4′ T5 28 W	25	0	0	0	0	25
9	3-lamp 4′ T8 fixture 36 W	3-lamp 4′ T5 28 W	17	0	0	0	0	17
10	2-lamp 5′ T8 fixture 58 W	2-lamp 5′ T5 35 W	23	0	23	0	0	0
11	PAR 30–35 W	CFL lamp 7 W	32	0	32	0	0	0
12	1-lamp 2′ T8 fixture 18 W	1-lamp 2′ T5 14 W	39	0	0	0	0	39
13	Incandescent 250 W	LED Bulb 12vW	11	0	0	0	0	11
14	4-lamp 4′ T8 fixture 36 W	4-lamp 4′ T5 28 W	29	0	0	0	0	29
15	125 W Mercury Vapor	LED Flood 10 W	42	0	42	0	0	0
16	HALOGEN 50 W–12 V	LED 7 W 12 V	42	0	42	0	0	0
17	Incandescent 60 W	LED Bulb 10vW (Non-dimmable)	41	0	0	0	0	41
18	No MAL	Motion Activated Lighting (MAL) Systems	3	0	3	0	0	0
19	No sensors	Motion sensors	62	0	62	0	0	0
20	Existing Dishwasher	New dishwasher	3	0	0	0	0	3
21	High flow showerheads	Low-flow showerheads	230	230	0	0	0	0
22	Existing washing machines	Energy Saving Washing machines	25	0	1	13	0	11
23	Existing Dryers	Energy efficient dryers	3	0	3	0	0	0
24	Existing Ironing Machines	Energy Efficient Ironing Machine	3	2	0	0	0	1
25	Pool pump	Eco pump	15	0	0	0	0	15
26	Existing Vending Machine	Energy Saving Vending machine	2	0	0	0	0	2
27	Old chillers	New chillers	2	0	0	0	0	2
28	Existing Aerators	Aerator upgrade	16	0	16	0	0	0

Table 6
Yearly selected measures ($w_1 = 0.7$, $w_2 = 0.2$, $w_3 = 0.1$).

j	Existing facility	Proposed alternative	y_j^1	y_j^2	y_j^3	y_j^4	Remaining
1	Poor power factor	Power-factor correction	0	0	0	0	1
2	No photovoltaic systems	Grid connected photovoltaic system	0	0	0	0	1
3	Existing HVAC system	More efficient HVAC	0	0	0	0	1
4	No solar water heater system installed	Installing roof mount solar water heater	0	1	0	0	0
5	No thermal pane glass	Double pane glass for building entrance	0	0	0	0	1
6	No irrigation system	Drip irrigation system	1	0	0	0	0
7	Existing toilets	Toilets replacement	0	0	0	0	1
8	Existing faucets	Faucets replacement	0	0	0	0	1
9	Existing urinals	Urinals replacement	0	0	0	0	1
10	No building energy meter installed	Building energy meter	0	0	0	0	1
11	No energy sub-system meter installed	Metering-energy subsystem	0	0	0	0	1
12	No building water meter installed	Building water meter	0	0	0	0	1
13	No building water subsystem meter	Metering-water subsystem	0	0	0	0	1

water savings increase for each consecutive year. The DPP obtained by the end of the project is 34 months, which is acceptable when compared to the project period of 48 months. The LEED certification level was obtained in the first year, LEED Silver certification was obtained in the second year, and LEED Gold was obtained in the third and fourth year.

It can be concluded that the weighting factors $w_1 = 0.7$, $w_2 = 0.2$ and $w_3 = 0.1$ can be used if the DM's main objective is to obtain the minimum points required for the various LEED certification levels. For the case studied, the project may be terminated by the third year as LEED certification is valid for five years, and based on the results obtained, the LEED gold certification level is already obtained by the third year. Hence no further retrofitting is required for the fourth year.

4.4. Varying the weighting factors

The objective functions are combined into one scalar function by applying constant weighting factors. These weighting factors can vary and is the choice of the DM. Table 7 illustrates the results obtained for various weighting factors, with a budget of [$15k, $45k, $80k, $350k] allocated to each year respectively. The results show the overall yearly retrofitting cost, which is the cost of installing facilities and measures; the yearly percentage energy and water savings incurred from the facilities retrofitted and the saving measures implemented; and the yearly LEED points based on the percentage energy and water savings incurred and the saving measures implemented.

When the weighting factors are set to $w_1 = 1$, $w_2 = 0$ and $w_3 = 0$ to emphasize minimization of the retrofitting cost, the yearly retrofitting cost incurred is [$3.36k, $42.5k, $56.2k, $0k] for each year respectively. No retrofit takes place in year 4 to minimize retrofit cost. The energy savings percentage obtained in the first year is 12%, but this is not sufficient in order to qualify for energy savings threshold points during the first year, as the minimum energy savings percentage required is 26%. There is no water savings obtained during the first year, and no saving measures are implemented. As a result, no LEED points are obtained from the energy and water efficiency categories during the first year. However, LEED certification is obtained as a result of points obtained in the other LEED categories. Furthermore, it is noted that the minimum points required for each certification level are obtained from the second year onwards (Silver: 50 points and Gold: 60 points). The DPP for this case is 26 months.

Table 7
Results comparison for different weighting factors.

w_1	w_2	w_3	Yearly costs ($)	Yearly energy savings (%)	Yearly water savings (%)	Yearly points	DPP (months)
1	0	0	[3k, 43k, 56k, 0k]	[12, 23, 34, 34]	[0, 37, 37, 37]	[45, 50, 60, 60]	26
0	1	0	[15k, 45k, 80k, 235k]	[19, 31, 41, 55]	[4, 55, 59, 74]	[45, 57, 67, 72]	29
0	0	1	[3k, 43k, 56k, 0k]	[12, 23, 34, 34]	[0, 33, 33, 33]	[45, 50, 60, 60]	24
0.7	0.2	0.1	[13k, 45k, 80k, 0k]	[19, 31, 41, 41]	[21, 55, 59, 59]	[48, 57, 67, 67]	34
0.2	0.7	0.1	[12k, 45k, 76k, 235k]	[19, 31, 41, 55]	[4, 55, 59, 74]	[45, 57, 67, 72]	29

With $w_1 = 0, w_2 = 1$ and $w_3 = 0$ to emphasize the maximization of LEED points, the yearly retrofitting cost incurred is [$15k, $45k, $80k, $235.36k]. The allocated funds for the first, second and third year are exhausted completely. The accumulative percentages of energy and water savings obtained by the end of the project are 55% and 74% respectively. The LEED points obtained during the final year of the retrofit is 72 points; this is 12 points more than the required points for LEED gold certification. The DPP for this case is 29 months.

When trying to minimize the DPP with $w_1 = 0, w_2 = 0$ and $w_3 = 1$, the yearly retrofitting cost incurred is [$3.3k, $42.5k, $56.2k, $0k]. The results obtained for energy savings, water savings and LEED points, are similar to the results obtained for when the weighting factors are $w_1 = 1, w_2 = 0$ and, $w_3 = 0$. There was no retrofit done in the fourth year. However, the payback period is 24 months, which is 2 months less than the payback period for when only the cost function is considered.

4.5. Sensitivity analysis with respect to input data

Some of the estimated energy savings from the retrofitted items as shown in Table 3 are from existing literatures or previous experiences. The accuracy of these unit energy savings figures could bring in uncertainties to the model in terms of the energy savings obtained by the model. In order to validate that the model output will not be severely affected by the accuracy of these savings figures obtained from literature, a sensitivity analysis is performed. The calculated energy savings input data for a selected number of facilities was varied in uniform increments, between −5% and 5%. The facilities considered for this sensitivity analysis were the chillers, ironing machine, dryers, power factor correction system and HVAC system, which are the main energy consumers.

It was observed from the model output that the selected number of facilities and saving measures results remained the same for the adjusted input data. With this 10% (−5% to 5%) change to the input data, the model output showed 2–4% change in the overall energy savings obtained by the model.

Since 10% estimation error is unlikely in the real case, i.e., the estimation of energy savings of facilities and measures are usually of good accuracy, we can conclude that the model result in terms of selected measures and facilities is robust against the unit energy savings input data and the result concerning overall energy savings by using the method proposed in this paper is not significantly affected by the unit energy savings estimation with an uncertainty range of ±5%.

5. Conclusion

This study presents an optimization model for an existing building retrofit in the energy and water efficiency categories. In addition to minimizing retrofitting costs, the model introduced green building certification as one of the objectives. Payback period is also considered by the model to help investment decision makers. Furthermore, the retrofitting project is implemented over several years to reduce the initial capital cost. The model can accommodate a wide range of facilities and measures within an existing building considered for retrofit. In order to demonstrate and evaluate the capabilities of the developed model, a case study of a hotel is presented. The results reveal that the model is able to produce an optimal retrofit plan that maximizes the benefits of retrofit and, at the same time, obtain green building certification under the Leadership in Energy and Environmental Design (LEED) rating system. The model presented also allows the decision maker indicate their preferences over certain performance indicators of the retrofit by means of weighting factors. In future work, the energy simulation tool (eQUEST)[7] can be incorporated for energy simulation analysis of the retrofitted building in order to obtain more precise energy savings and hence energy savings threshold points. In addition, this model only considered retrofitting in two LEED categories, the problem can be expanded to include retrofitting opportunities in the remaining categories of LEED.

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