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AN OPTIMAL MODEL FOR A BUILDING RETROFIT WITH LEED STANDARDS AS REFERENCE PROTOCOL

by

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SUMMARY

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Keywords:	Building retrofit, energy savings, green building certification, multi-objective optimization, water savings.

This research study presents a multi-objective optimization model aimed at optimizing the retrofitting costs, energy savings, water savings, pay-back period and points earned under the Leadership in Energy and Environmental Design (LEED) rating system. In order to assist the decision-makers (DM) with the appropriate selection of facilities, 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. The contribution of this research study is that the percentage energy and water savings of each retrofitting facility or measure is identified, and the LEED points obtained as a result of the energy and water savings is considered, and in the process LEED certification is obtained. The issue of limited available funds is also considered as the retrofitting project is implemented over several years, enabling the DM to reinvest savings from preceding years and reduce the initial investment. Consequently, the time value of money is considered by applying the discounted payback period (DPP). A sensitivity analysis is performed by analyzing the influence of the weighting factors applied to each objective function. The results reveal that the weighting factors have a great influence on the number of selected facilities, selected energy and water saving measures, and the project cost.

A case study of a hotel in South Africa is presented to demonstrate the feasibility of the

proposed model and optimization approach. The optimization results show the optimal number of selected facilities and measures for each year. The cost associated with the project ranges between $13k-$140k for each year respectively, and an increase in the percentage of energy and water savings is noted for each consecutive year. For the case studied, LEED gold certification level is achieved by the end of the project, and the payback period is 34 months.

OPSOMMING

’N OPTIMALE MODEL VIR ’N GEBOURETROTOEVOEGING MET DIE LEED- STANDAARD AS VERWYSINGSPROTOKOL

deur

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Hierdie navorsingstudie bied ’n meervoudige doelwit optimalisering model aan, gemik op die optimalisering van die installasiekoste, energiebesparing, waterbesparing, terugbetaaltydperk en punte verdien onder die Leierskap in Energie en Omgewing Ontwerp (LEED) gradering stelsel. Ten einde besluitnemers te help met die geskikte keuse van fasiliteite, neem die ontwikkelde model ?n wye verskeidenheid van fasiliteite en spaar maatreëls in ag as retrofit alternatiewe vir die energie- en waterdoeltreffendheid kredietkategorieë van LEED. Die bydrae van hierdie navorsing is dat die LEED puntebydrae van elke fasiliteit of maatstaf oorweeg word en LEED sertifisering in die proses verkry word. Daarbenewens is die bestaande modelle verbeter deur beide die LEED drempel en afmerkpunte te oorweeg. Die probleem van beperkte beskikbare fondse word ook inaggeneem deur die retrofitprojek oor ’n tydperk van ’n paar jaar te implimenteer en die besluitnemers sodoende in staat te stel om besparings van die voorafgaande jaar te herbelê en die aanvanklike belegging so te verminder. Gevolglik word die tydswaarde van geld beskou deur die toepassing van die verdiskonteerde terugbetalingstydperk. ’n Sensitiwiteitsanalise word uitgevoer deur die ontleding van die invloed van die gewigsfaktore op elke doelfunksie toe te pas. Die resultate dui daarop dat die gewigsfaktore ’n beduidende invloed op die die aantal gekose fasiliteite en die projekkoste het.

'n Gevallestudie van 'n hotel in Suid-Afrika word aangebied om die haalbaarheid van die voorgestelde model en optimalisering benadering te demonstreer. Die optimalisering resultate toon die optimale aantal gekose fasiliteite en maatreëls vir elke jaar aan. Die koste verbonde met so 'n projek wissel tussen \$13k - \$140k per jaar en 'n toename in die persentasie energie- en waterbesparing word gemerk vir elke daaropvolgende jaar. Vir die gevallestudie is die LEED goud sertifisering vlak behaal teen die einde van die projek en die terugbetalingstydperk is 34 maande.

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NOMENCLATURE

i	facilities or fixtures to be retrofitted
n	number of facilities available for retrofitting
j	energy or water saving measure
m	represents the number of saving measure alternatives
T	retrofitting project period
t	retrofitting year
x_i^t	quantity of the selected type i facilities to be retrofitted in year t
y_j^t	type of saving measure implemented in year t
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
P_E^t	energy savings LEED points
P_W^t	water savings LEED points
P_j	saving measure LEED points
BEC	building energy consumption
BWC	building water consumption

LIST OF ABBREVIATIONS

EA	Energy and Atmosphere
CDCF	Cumulative Discounted Cash Flow
DCF	Discounted Cash Flow
DM	Decision Maker
DPP	Discounted Payback Period
GBCSA	Green Building Council of South Africa
LEED	Leadership in Energy and Environmental Design
LEED-EB	LEED Existing Building
MINLP	Mixed Integer Non-Linear Programming
MOO	Multi-Objective Optimization
NPV	Net Present Value
USGBC	U.S. Green Building Council
WE	Water Efficiency

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

1.1.1 Problem in context

ESKOM, South Africa's premier electricity supplier, began load shedding in 2008 as it battled to meet the country's energy demand [1]. As a result, the gross domestic product (GDP) dropped by 3.83% during the first quarter of 2008 [1, 2]. In 2004, ESKOM introduced nationwide campaigns, demand side management programs, and energy rebate projects as a short term solution to the energy crisis. This accounted for a 15% annual reduction in electricity consumption by 2012 [2] [3]. However, the country remains in an energy crisis which is estimated to continue for the next 5 years, creating a major threat to the country's economy. Hence, a widespread retrofitting strategy of existing buildings can be implemented as a long term solution to South Africa's energy crisis.

Retrofitting of existing buildings is a fast and cost effective intervention to reduce energy consumption. Other benefits resulting from this intervention include: reduced operating costs, occupant comfort, and reduced negative environmental impacts [3, 4]. 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.

[1] Understanding the current energy crisis in South Africa http://www.theoildrum.com/node/3576

[2] Eskom's energy retrofits of multiple office blocks and engineering workshops in Cape Town ÂŰ a shining example https://www.capetown.gov.za/en/EnvironmentalResourceManagement

[3] Prepare for power load shedding which could last 12 hours http://www.environment.co.za/southafricasenergycrisispreparefor powerloadsheddingwhichcouldlast12hours

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, uncertainty of economic and environmental benefits as well as the interdependence between the sub-systems of a building [5]. In light of South Africa's energy crisis and the high percentage of existing buildings which do not comply with the environmental sustainability standards, the Green Building Council of South Africa (GBCSA) predicts an increase in refurbishments of existing buildings [4]. Consequently, South Africa has become one of the fastest growing green building market in the world [5]. The Green Star rating system which is an Australian based rating system is currently used in South Africa. LEED is chosen as the rating system for this research study because it is adaptable to a wide range of project types and can be adopted globally, whilst Green Star predicts the building performance from a single building model. In addition, LEED considers a larger number of parameters for assessing the building performance[6]. Furthermore, LEED has a higher standard than Green Star in terms of energy efficiency[6]. The LEED projects completed in South Africa include MTN's head office in Johannesburg, Menlyn Maine in Pretoria and Hotel Verde in Cape Town (which is the first platinum certified building in Africa).

1.1.2 Research opportunity

Research studies focussed on multi-objective optimization (MOO) models for building retrofits have been developed. However, with the emergence of green buildings and the implementation of carbon tax, there is a need to incorporate green building certification in existing building retrofits. This research study introduces a MOO model for the selection of retrofit measures in an existing building. In addition, the model aims to select the optimal number of facilities and measures in order to qualify for LEED green building certification. Only retrofitting actions related to the energy and water efficiency LEED categories were considered, as the point contribution of these to categories is 50% of the maximum available LEED points.

[4] South Africa's strong case for green retrofitting http://www.moneyweb.co.za/uncategorized/southafricasstrongcaseforgreenretrofitting

[5] Addressing South Africa's energy crisis with a long term solution http://www.securitysa.com/50731n

[6] https://docs.google.com/document/d/14UDP4qZA23EsaF4bOBr8AURMvDPko8k7V5fl07eml7g/preview

1.2 RESEARCH OBJECTIVE AND QUESTIONS

The objective of this research study is to introduce a multi-objective optimization (MOO) model for the optimal selection of retrofit measures in an existing building. In addition to simultaneously minimize costs, maximize energy and water savings, and minimize the payback period, the model aims to select the optimal number of facilities and measures in order to qualify for LEED green building certification.

The research questions are as follows:

- How can LEED green building certification be achieved through the proposed model for existing building retrofits?
- How does the function weighting factors affect the model?
- What is the nature of the number of selected facilities over the period of the project?
- What are the costs and the payback period associated with such a project?

1.3 HYPOTHESIS AND APPROACH

It is hypothesized that the implementation of the above mentioned multiple-objective optimization model will result in optimally selected facilities and measures for retrofit, energy and water efficiency improvement, green building certification, reduced operating costs, and building sustainability.

In order to achieve the objectives of the MOO model, the approach to be followed is as follow:

1. Literature study - A literature study is conducted on the optimization of building retrofits for energy and water efficiency.
2. Development of an optimization model - A mathematical model characterizing the building to be retrofitted such as the objectives, decision variables and constraints is developed.

3. Simulation and results - The model is implemented by using a Matlab based algorithm.

4. Case study and analysis - The applicability of the model is presented through a case study of an existing building.

5. Results and analysis - The simulated results are presented and discussed, and the retrofits which result in the minimum retrofitting cost, LEED certification and the minimum payback period is chosen as the options leading to the optimal solution.

The remainder of the dissertation is structured as follows: In Chapter 2, a literature review on the work relevant to this study is presented. In chapter 3, the MOO model is presented, and applied to a case study in chapter 4. In Chapter 5, the results of the case study are presented and analyzed. In chapter 6, the results are discussed, and in chapter 7 this work is concluded.

CHAPTER 2

LITERATURE STUDY

In this chapter a literature study for existing building retrofits for energy and water efficiency is performed. Furthermore, optimization models for existing building retrofits are also discussed. Finally, models incorporating point based standards are discussed in detail.

2.1 HOTEL BUILDING RETROFITS

When compared to other types of public buildings, hotel buildings generally consume more energy and water for the following reasons: the operation of a hotel has distinct characteristics which directly affect the energy and water consumption, hotels have different functional areas and facilities, and hotels operate for an entire day. Hence, continuous operation of equipment and services are required. Hotels also have a high occupancy rate[7]. As a result, a great opportunity for energy and water efficiency improvement is identified. This research study hence focuses on the energy and water efficiency retrofit of an existing hotel building. In addition, green building practices for building retrofits are considered and LEED green building certification is achieved [8].

2.1.1 Energy conservation measures

A hotel's energy consumption pattern may vary and is dependent on the age, size and class of the building. Old hotels for example consume more energy as a result of the deterioration of the building's structural material (eg.wall insulation). The large and high classed hotels requires continuous hot water production and use large equipment in the kitchen and laundry. Furthermore, the behavior of the building's occupants also have an impact on the energy consumption [9].

Existing lighting fixtures can be replaced with new lighting technologies such as the compact fluorescent lamps (CFL's)and LED lamps in order to reduce energy consumption. In addition, the use of motion activated lighting systems also contribute to energy savings [10]. In a hotel, the bathroom is generally separated from the guest room. Since movement in the bathroom is minimal, occupancy sensors can be used, hence, false triggering of the sensors can be avoided. Hotel guests are generally not too cautious about energy savings in a hotel, and often forget to switch off the lights. As a result, bathroom lighting fixtures consume the most energy during the day, operating for an average of 8 hours a day [11].

Hotel buildings operate for 24 hours a day, continuous production of hot water is thus required. Water heating systems in a hotel, hence consume the most energy. Heat pumps offer an energy-efficient way to heat water, and can save between $30 - 35\%$ of the energy. Hotel laundering, specifically for guest room sheets and towels also consume a lot of energy. Energy efficient washing and ironing machines can be implemented in order to reduce energy consumption. In addition, laundry scheduling can be applied in order to avoid the use of laundry equipment during peak hours. Fig 2.1 shows the energy conservation methods which can be applied in order to reduce the hotel's energy consumption. It is evident that retrofitting of existing facilities will result in the highest energy savings.

2.1.2 Water conservation measures

The hotel guest rooms consume the most water as a result of inefficient plumbing fixtures in the building. In order to save water, bedroom shower heads and facets can be replaced.

2.2 OPTIMIZATION MODELS FOR EXISTING BUILDING RETROFITS

Identifying facilities and saving measures to undertake during a building retrofitting project can be a challenging task for the decision maker (DM). This is due to conflicting interests such as costs, energy savings, water savings, environmental impacts, cost benefits and human comfort [12, 13]. As a result, multi-objective optimization models (MOO) and green building rating systems have been used to assist the DM [14]. Similarly, other decision aid approaches

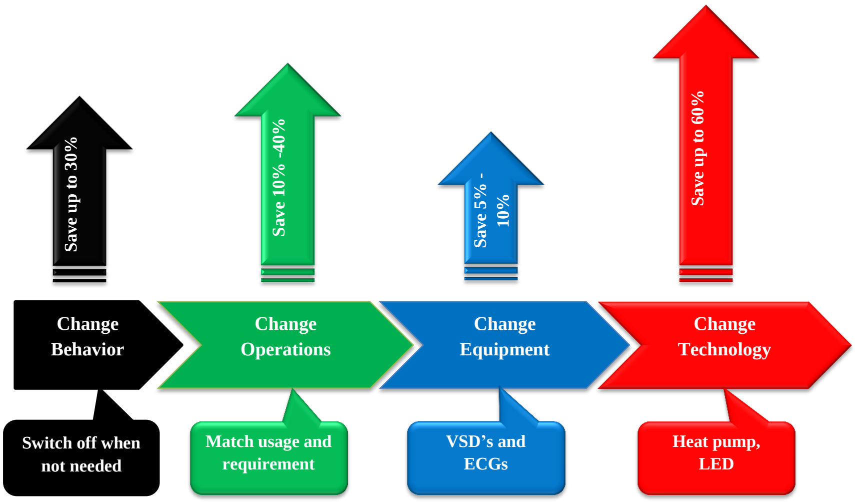

Figure 2.1: Types of energy conservation methods

such as multi-criteria (MC) analysis [15] and cost-benefit analysis [16, 17, 18, 19, 20] 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 is discussed in [21]. The aim of the model is to simultaneously minimize costs and maximize energy savings, through the assessment of alternatives for each retrofit action. In addition to the model presented in [21], a third objective (maximising thermal comfort) was proposed in [22]. A research study was further conducted to investigate the feasibility of the afore mentioned model using genetic algorithms (GA), and artificial neural networks (ANN). Following that, the results quantified the impact of each retrofit action on the buildings overall performance [23].

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 are presented in [24, 25, 26, 27]. The results of [24] show the feasibility and benefits of applying multi-objective optimization techniques to energy efficiency improvement retrofits. Consequently, it has become common for DM's to use simulation based techniques. However, since the aim of these techniques are to overcome the model constraints, the DM is limited to a range of options [26]. In contrast to this, a model presented in [25] 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 [25]. 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 [28]. Apart from energy simulation methods, green building rating systems such as LEED were used as reference when selecting retrofitting measures [13, 29, 30]. 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 [13] and [31], a model is presented for the selection of building materials (roofs, carpets, paint, glass and wood). The model aims to maximize the points obtained under LEED, while the design and budget constraints are met. The results show that the points achieved under LEED are not only affected by the budget, but the design constraints as well [13, 12]. It also shows the relevance of allocating points in order to meet the design constraints.

Apart from selecting retrofit actions that will result in maximum energy savings and minimum costs, successful retrofit solutions should also minimize their negative impacts on the environment. As a result, MOO models focused on selecting retrofit measures to minimize environmental impacts, while budget constraints are met have been developed [32, 33]. On many occasions, building owners and managers are hesitant to participate in building retrofitting projects due to economic uncertainty. Considering the case in point, 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 [34] aims to simultaneously maximize energy savings and minimize the payback period. The results showed that the energy savings and the payback period are directly affected by the initial investment. Futhermore, a model was developed considering the maintenance costs associated with the retrofitted facilities. The results of the afore mentioned model demonstrated that it is more cost-effective to incorporate maintenance costs for a better life-cycle cost analysis [35].

2.3 LEED STANDARDS

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 [36]. 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 [37, 38]. The LEED certification program also strikes a good balance between known, established, and new concepts. The green building rating system used in South Africa is the Green Star rating system which is based on the Australian system. However, the LEED green building system is becoming popular in South Africa. The LEED projects completed in South Africa include MTN's head office in Johannesburg, Menlyn Maine in Pretoria and Hotel Verde in Cape Town (which is the first platinum certified building in Africa).

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 (SS), Water Efficiency (WE), Energy Atmosphere (EA) and Materials & Resources (MR). A maximum of 100 points are available from the above mentioned categories, but an additional 10 points can be obtained from the Innovation in Operations (IO) and Regional Priority (RP) credit categories. Each LEED point is a positive integer. 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)[39].

2.3.1 LEED: Energy and water efficiency categories

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 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 on the basis that the building's water and energy consumption is measured, commissioning is done, recycling management programs are in place and the reporting of carbon dioxide emission. The LEED-EB credits identified for the building retrofit and their respective facilities or measures are shown in Tables 2.1 and 2.2.

Table 2.1: The WE and EA threshold point credit categories (USGBC, 2012)

Topic	Credit	Description	Retrofits / Measure	Points
WE	Credit 1	Outdoor water use reduction	High efficiency irrigation systems	1 – 2
			Irrigation system meters	
WE	Credit 2	Indoor water use reduction	showers,dish washers	1 – 5
			toilets, urinals	
			faucets and automatic controls	
EA	Credit 4	Optimize Energy Performance	Motion sensors	1 – 20
			energy efficient lamps	
			low-flow shower heads	
			heater wraps, heat pumps	
			power factor correction	
			chillers, control systems	
			renewable energy, aerators	
			solar water heating system	
			variable frequency drives	
	Credit 7	Renewable Energy and Carbon Offsets	Solar, geothermal, wind	1 – 5
			biomass systems	
		MAXIMUM THRESHOLD POINTS		**1-32**

Table 2.2: The WE and EA check-off point credit categories (USGBC, 2012)

Topic	Credit	Description	Retrofits / Measure	Points
WE	Credit 3	Cooling Tower Water Use	Water chemical treatment system	2 – 3
			backwash water system	
	Credit 4	Water Metering	Building-level water meter	1 – 2
			sub-system water meter	
EA	Credit 5	Advanced Energy Metering	Building-level energy meters	2
			sub-system energy meters	
	Credit 6	Demand Response	Fully automated demand response system	1 – 3
			Semi-automated demand response system	
			Electrical load shifting measures	
	Credit 8	Enhanced Refrigerant Management	HVAC and refrigeration system	1
		MAXIMUM CHECK-OFF POINTS		**1-11**

2.4 RESEARCH GAP

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. The model developed in [12] and [13] considered the design, budget and LEED requirements for materials selection. In addition, although the model aimed to maximize the number of LEED points, the maximum points obtainable were not sufficient to ensure green building certification. A model aimed to maximize the awarded threshold points for material selection of a carpet system, during the manufacturing process is presented in [31]. However, check-off points were not considered. In light of the economic viability of retrofitting projects, the simple payback period is used in [34] and [35] to determine the return on investment for a fixed initial investment.

This research study introduces a MOO model for the selection of retrofit measures in an existing building. In addition to simultaneously minimizing costs and maximize energy, the model aims to select the optimal number of facilities and measures in order to qualify for LEED green building certification. The unique contribution of this research study is that the LEED point contribution of each retrofitting facility or measure is considered. In order to maximize the points required for LEED certification, retrofitting facilities and measures were identified for the energy and water efficiency categories. These categories contribute up to 50% of the available points. Furthermore, both the threshold and check-off points are considered. Limitation of available funds is also considered, the retrofitting project is implemented 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). The decision variables represent a selection of facilities for energy and water efficiency. The maximum number of each type of facility available, LEED certification levels, and budget are applied as constraints. In summary, this work demonstrates the applicability of LEED existing building (LEED-EB) standards as a reference tool when identifying measures to reduce energy and water consumption in an existing building. The optimal results are the optimal number of facilities and measures that will result in minimized retrofitting costs, maximum LEED points and a minimum payback period.

2.5 CHAPTER SUMMARY

A literature study on the energy demand and water demand of hotel buildings is presented. The opportunities for retrofits in hotels are identified, and their energy and water saving contributions are given. Furthermore, the existing optimization models for building retrofits are discussed, and the contribution of this research is given. The following chapter introduces the model developed for this research study.

CHAPTER 3

MODEL FORMULATION

3.1 THE MULTI-OBJECTIVE OPTIMIZATION MODEL

This section presents the proposed multi-objective optimization model for an existing building retrofit. The decision variables, objective functions, constraints and the optimization technique involved in the problem are thus defined. The decision variables concerns energy and water efficiency measures and facilities to be retrofitted and installed to a building. All constraints concerning the decision variables and their relations are considered. Non-linear mathematical formulations are used to define the objectives. The model will help the decision-makers to identify/determine an optimal retrofit and installation plan in order to meet the defined objectives.

3.1.1 The decision variables

The decision variables defined 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: threshold points and check-off points. The first category concerns retrofitting of the building's equipment and fixtures which consume 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 [32].

The retrofitting project is implemented over several years. This will allow the decision maker to make the best use of the available funds. Let i represent the facility index of the first category (this is the type of facilities or fixtures to be retrofitted), and n represent the number of facilities available for retrofitting ($i = 1, 2, \ldots, n$). The decision variable of this category is an integer denoted by x_i^t, indicating the quantity of the selected type i facilities to be retrofitted, during year t of the project, where t ($t = 1, 2, \ldots, T$) denotes the number of years in the project.

Let j represent the index of measures concerning the second category, and m ($j = 1, 2, \ldots, m$) represents the number of alternatives available for category two. The decision variables concerning the second category are binary variables y_j^t which either take on the value of 1 or 0, corresponding to whether or not a saving measure is implemented, as shown below:

$$y_j^t = \begin{cases} 1, & \text{if energy or water saving measure } j \text{ is implemented in year t;} \\ 0, & \text{if energy or water saving measure } j \text{ is not implemented in year t.} \end{cases} \tag{3.1}$$

The cost of facility i and measure j during year t is denoted by c_i^t and d_j^t. The percentage energy and water savings achieved by retrofitting one unit of facility i, or implementing measure j are es_i, ems_j, ws_i and wms_j. The cost of energy and water in a specific year is denoted by ec^t and wc^t. The number of LEED points earned for the percentage energy and water savings are denoted by: $P_E^t + P_W^t$ and that earned for implementing the $j-th$ measure is denoted by P_j. The total number of decision variables are therefore $((n+m).T)$ and concerns alternative choices regarding:

- the energy and water consuming facilities and fixtures to be retrofitted: $i = 1, 2, \ldots, n$;
- the energy and water saving measures and renewable sources to be implemented: $j = 1, 2, \ldots, m$;
- the quantity of type i facility to be retrofitted during each year: x_i^t;
- the energy or water saving measure to be implemented during each year: y_j^t;
- the energy or water savings obtained due to a retrofit: es_i, ems_j, ws_i and wms_j; and
- the LEED threshold and check-off points obtained: P_E, P_W and P_j.

The decision variables defined above are denoted by a vector X, where

$$X = [x_1^1, x_1^2, \ldots, x_1^T, x_2^1, x_2^2, \ldots, x_2^T, \ldots, x_n^1, x_n^2, \ldots, x_n^T, y_1^1, y_1^2, \ldots, y_1^T \ldots, y_m^1, \ldots, y_m^T]^T. \quad (3.2)$$

For simplicity, only one technology is considered for each type of facility or measure. The cost of each facility increases yearly and is dependent on the yearly interest rate. The model assumes that all the LEED prerequisites are met and that points are allocated based on the percentage energy and water savings incurred, as well as the measures undertaken. The points allocated are based on LEED for Existing Buildings [1]. It is assumed that the same LEED version is applicable to $t = 1, 2, \ldots, T$.

3.1.2 Objective functions

The objectives of the optimization model are to minimize retrofitting costs, maximize LEED points, and to minimize pay back period. A mathematical representation of these three objectives are provided in the subsequent contents.

3.1.2.1 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 for the project period as follows:

$$F_1(X) = \sum_{t=1}^{T} \left(\sum_{i=1}^{n} x_i^t . c_i^t + \sum_{j=1}^{m} y_j^t . d_j^t \right). \quad (3.3)$$

3.1.2.2 LEED points

In order to qualify for LEED certification, all prerequisites must be met, and a minimum of 40 points must be obtained. The LEED credit categories considered for this model are defined in Tables 2.1 and 2.2. The building's yearly baseline energy and water consumption is denoted by (BEC) and(BWC) respectively. The yearly energy and water savings incurred from the retrofit are calculated as follows.

$$ES^t = \frac{\sum_{k=1}^{t} (\sum_{i=1}^{n} x_i^k . es_i + \sum_{j=1}^{m} y_j^k . ems_j)}{BEC}. \quad (3.4)$$

[1] LEED v4 for Operations & Maintenenace:Existing Buildings

$$WS^t = \frac{\sum_{k=1}^{t}(\sum_{i=1}^{n} x_i^k.ws_i + \sum_{j=1}^{m} y_j^k.wms_j)}{BWC}. \tag{3.5}$$

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

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

and

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

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:

$$F_2(X) = F_2^0 + P_E^t + P_W^t + \sum_{j=1}^{m} y_j^t.P_j, \tag{3.6}$$

where: F_2^0 are the points obtained in the other LEED credit categories, P_E^t and P_W^t are energy and water savings threshold points respectively, and $\sum_{j=1}^{m} y_j^t P_j$ are check-off points obtained by implementing a measure in year t.

3.1.2.3 Payback period

Building owners and managers often hesitate to invest in retrofitting projects due to the uncertainties of financial benefits. This requires for a closer look at the financial performance of existing building retrofitting projects, as the implementation of such projects becomes more attractive once the payback period (PP) is known. The building retrofitting project is implemented over several years, therefore the time value of money has to be considered by applying the discounted payback period (DPP). Unlike the simple payback period, the DPP calculates the present value of each cash inflow by taking the initial period as zero point. The DPP is calculated as [40]:

$$F_3(X) = DPP = t^- + \frac{|CDCF_-^t|}{DCF^{t+1}}, \tag{3.7}$$

where: t^- is an integer and is 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^-. Assuming that the building retrofit is implemented at the beginning of each year, the variables in Eq.(3.7) are defined as follows.

$$CF_{in}^t = \sum_{i=1}^{n} x_i^t (es_i^t ec^t + ws_i^t wc^t) + \sum_{j=1}^{m} y_j^t (ems_j^t ec^t + wms_j^t wc^t), \tag{3.8}$$

$$CF_{out}^t = \sum_{i=1}^{n} x_i^t.c_i^t + \sum_{j=1}^{m} y_j^t.d_j^t, \tag{3.9}$$

$$CF^t = CF_{in}^t - CF_{out}^t, \tag{3.10}$$

$$DCF^t = \frac{CF^t}{(1+d)^t}, \tag{3.11}$$

and

$$CDCF^t = CDCF^{t-1} + DCF^t. \tag{3.12}$$

where Eqs.(3.8) and (3.9) define the cash inflow and outflow at year t. The total discounted cash flow in year t is shown in Eq.(3.11), where d is the discount rate. The CDCF is shown in Eq.(3.12).

3.1.3 Constraints

The model aims to maximize LEED points, while minimizing costs as well as the payback period. For the practicality of the model, the decision maker (DM) must know what can be feasibly achieved by defining constraints. This results in the feasibility plane, 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 the model constraints are implemented yearly. The optimization model constraints are:

$$\sum_{t=1}^{T} x_i^t \leqslant z_i, \tag{3.13}$$

$$y_j^t \in \{1, 0\} \ \forall \ j = 1, 2, \ldots, m \text{ and } t = 1, 2, \ldots, T, \tag{3.14}$$

$$\sum_{i=1}^{n} x_i^t.c_i^t + \sum_{j=1}^{m} y_j^t.d_j^t \leq \beta_t, \tag{3.15}$$

$$F_2^t(X) = F_2^0 + P_E^t + P_W^t + \sum_{j=1}^{m} y_j^t.P_j \geq \rho_t, \tag{3.16}$$

and

$$NPV = CF_0 + \sum_{t=1}^{T} \frac{CF^t}{(1+d)^t} \geq 0, \tag{3.17}$$

where:

- z_i - Maximum quantity of each type of facility
- β_t - Budget in (\$) for each year t

- $F_2^t(X)$ - Points obtained in year t
- ρ_t - LEED point target for each year t
- NPV - Net present value at the end of the project

The decision variable constraints are defined in (3.13) and (3.14). Due to a limitation in funds available, Inequality.(3.15) defines the retrofit project budget constraint, where β_t is the budget allocated to the retrofit project in year t. 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 (3.16), where ρ_t is the LEED point target for each year. The constraint in (3.17) is applied to ensure that the net present value (NPV) is always positive. A positive net present value indicates a positive difference between the initial investment and the discounted cash payments of the subsequent years (at the reference point of year 0), which then yields a financially attractive project.

3.2 MODEL IMPLEMENTATION

3.2.1 Aggregated objective function

This research study considers a MOO model for an existing building retrofit within the energy and water efficiency categories. The model is formulated as a mixed integer non-linear programming (MINLP) problem for the optimal selection of retrofitting facilities and measures. Due to the nature of the problem, the objective functions 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. The aforementioned method combines the multiple objectives into one scalar function by applying a constant weight coefficient to each function [41, 42]. With the objective functions defined, the aggregated objective function employed in this study can be written as:

$$J = w_1 F_1(X) - w_2 F_2(X) + w_3 F_3(X). \tag{3.18}$$

where $w_k (k = 1, \ldots, 3)$ is the weighting factor, and $0 \leq \sum_{k=1}^{3} w_k \leq 1$ is satisfied.

3.2.2 Optimization approach

The formulated problem is an MINLP problem according to the decision variables x_i and y_j. MINLP problems can be solved with optimization solvers such as SCIP, CPLEX and IBM. For the problem in this study, the basic open-source mixed integer (BONMIN) solver, which is compatible with Matlab is used. BONMIN's branch-and-bound (BB) algorithm, which solves for a continuous non-linear program at each node of the search algorithm, is used due to its optimal properties and solution convergence time [43, 44]. The optimization procedure for the optimal selection of retrofitting facilities and measures is shown in Fig.3.1. The developed Matlab program imports the decision variable data from an excel spreadsheet. The data is first analysed, then the selection procedure starts for the type of facilities, number of facilities, and measures to be implemented.

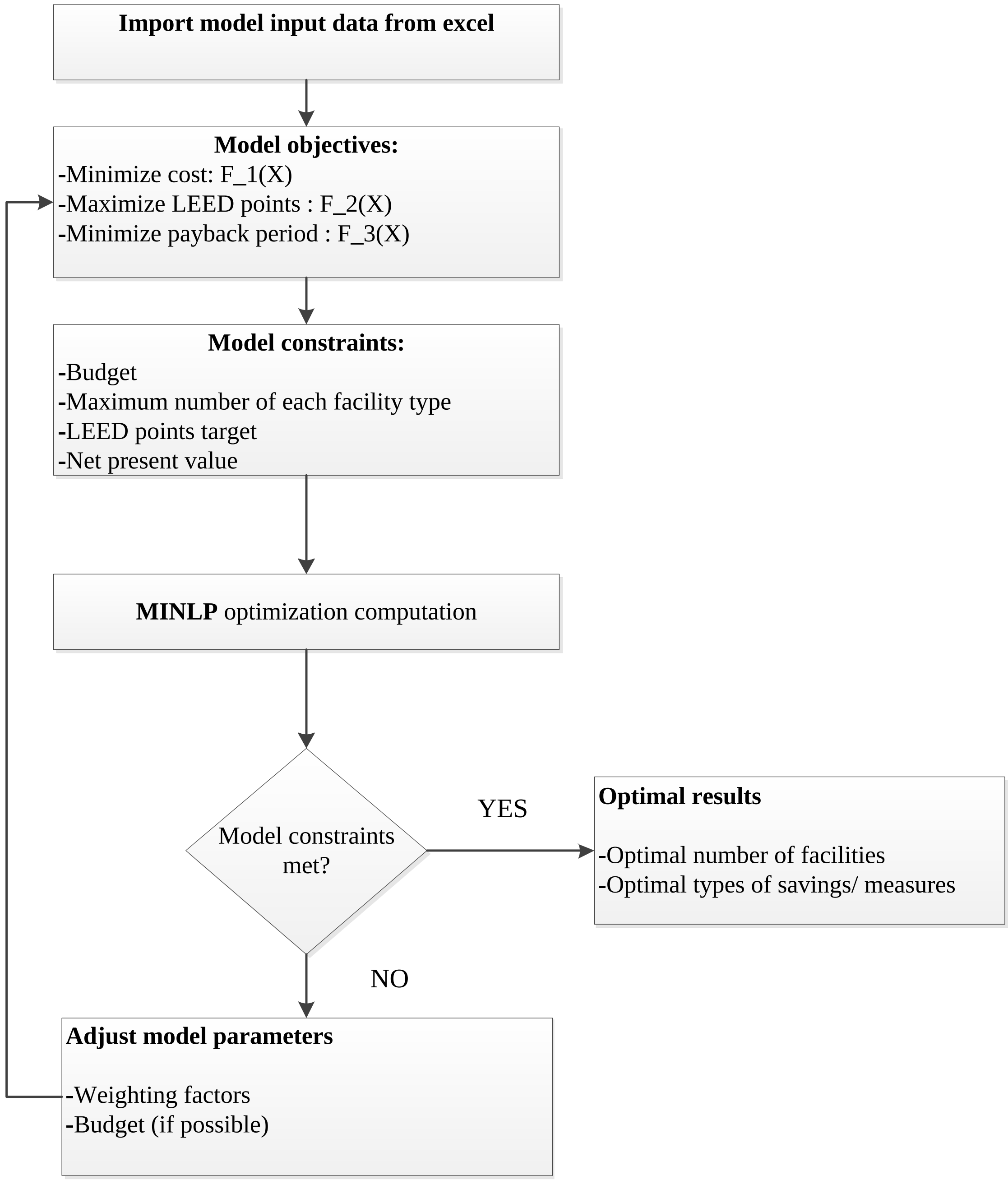

Figure 3.1: The optimization flow chart

3.3 CHAPTER SUMMARY

In this chapter, the formulation for the multi-objective optimization model is presented. The model decision variables are the facilities to be retrofitted and saving measures to be implemented. Each decision variable (facilities and measures) has a maximum quantity, cost of retrofit, energy savings and water savings associated with it. The objectives of the model are: to minimize retrofitting cost; to maximise LEED points and to minimize the payback period. The objective functions are combined in one cost function by implementing the weighted sum approach. The model is implemented over several years, the retrofitting budget and LEED point target for each year is thus defined as the model yearly constraints. Furthermore, the maximum number of facilities available for every facility type is defined as a constraint for the overall project period. In the following chapter, a case study of an existing hotel building is presented and the model input parameters are given.

CHAPTER 4

CASE STUDY

The objective of this chapter is demonstrate the applicability of the developed theoretical model to a real-world project. Firstly, a description of the case study building and its installed facilities is given. Secondly, the proposed alternatives for the existing facilities and measures are shown, and finally, the input parameters for the case study are given.

4.1 BUILDING DESCRIPTION

For the applicability of the developed MOO problem, an existing building is analysed and used as a case study. The building under study is a hotel, located in Pretoria, the administrator capital city of South Africa. The hotel was built in 1987, and its last renovation was in 2014. The building consists of 15 floors: the first floor consists of parking lots, storage and laundry rooms; the second floor consists of the reception area, rest area, men's bathroom, women's bathroom, lobby, vending machine, conference rooms, kitchen, dinning area, swimming pool and bar area. The rest of the building floors consist of guest rooms. The building operates 24 hours a day throughout the week and has an average occupancy rate of 60% [1]. The laundry equipment, HVAC, lighting and water heating systems are the main contributors of energy consumption as shown in Fig.4.1. In Fig.4.2 the main contributors of water consumption are the laundry equipment and the equipment in the bedrooms (toilets, bathtubs and showers). There are occupancy controls in two storerooms which controls the switching on off light to save energy. These are the only controls installed in the building. The building's energy

[1]South African tourist accommodation statistics release http://www.statssa.gov.za/publications/P6410/P6410October2014.pdfhttp://www.statssa.gov.za/publications/P6410/P6410October2014.pdf

charge is based on the time of use tariff (TOU). 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 data of Figs.4.1 and 4.2 were obtained from the hotel's energy audit.

Table 4.1 shows the energy and water consumption and utility rates as well as the discount rate and interest rate for economic analysis. On a global scale, South Africa's electricity prices still compare favorably. However its yearly energy price increase is the highest, and it is estimated that it will continue to be the highest for the next five years as a result of the current energy crisis [45]. This is one of the most important driving forces for existing building energy efficiency retrofit.

Table 4.1: Hotel annual electricity and water consumption, utility rates, and discount rate.

Building performance indicator	Rate
Annual energy consumption	22,409,66 kWh
Average electricity billing rate	0.13 $/kWh
Annual water consumption	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%

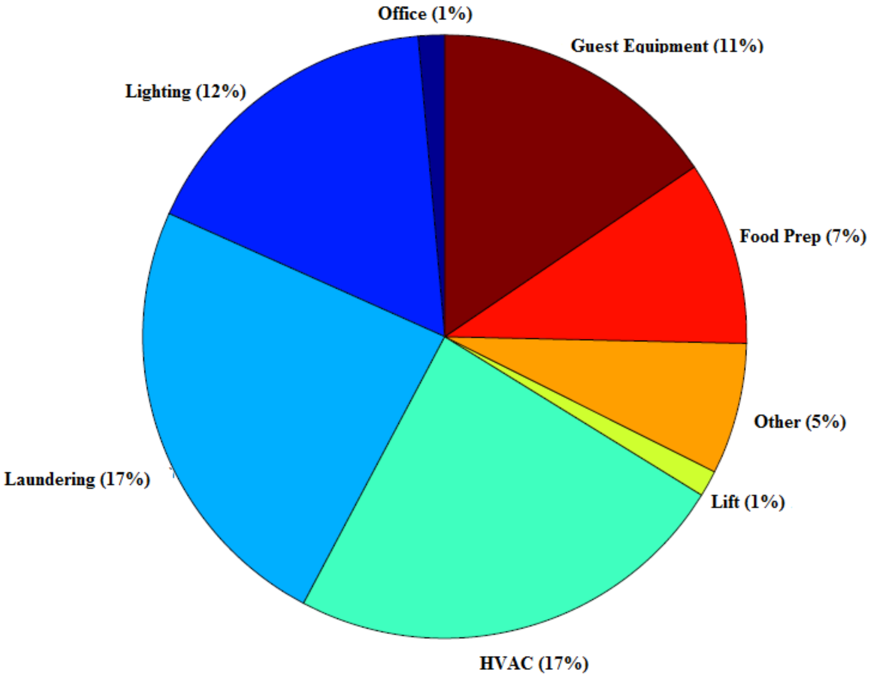

Figure 4.1: Hotel energy consumption breakdown

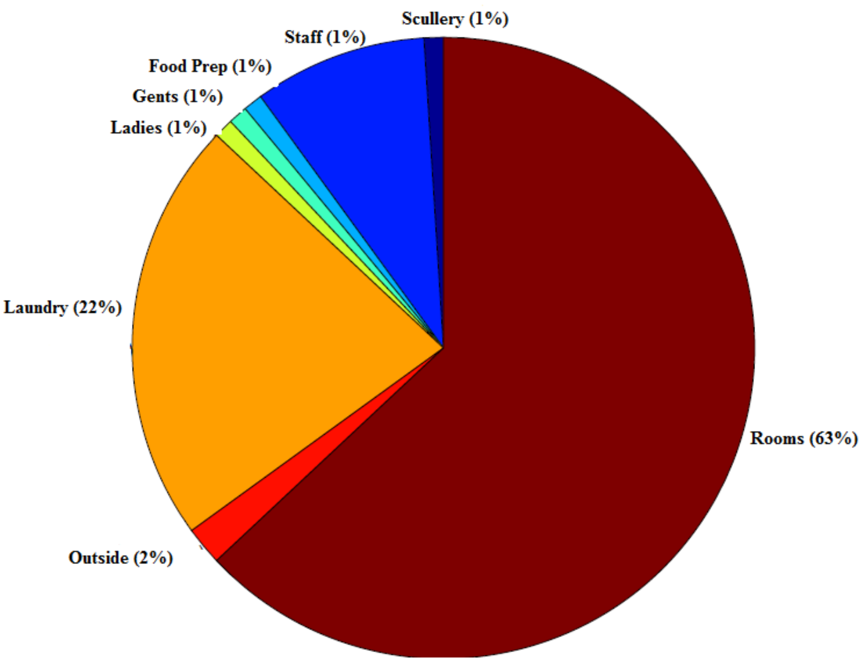

Figure 4.2: Hotel water consumption breakdown

4.2 DATA COLLECTION

For data collection, a site visit was conducted, and data was also obtained from the energy audit of the hotel. The hotel's main source of energy and water is electricity supplied by the local municipality.

4.2.1 Hotel energy audit

The electricity consumption patterns of the heat pumps, kitchen and laundry are shown in Figs. 4.3, 4.4, and 4.5. It is evident that there is continuous energy demand from the heat pumps and the kitchen. The heat pumps are designed to be switched on continuously in order to supply the cheapest heat, and the kitchen's electrical facilities operate continuously for the daily preparation of meals. The kitchen's energy demand is the lowest when only the storage rooms are switched on. The heat pumps consume an average of 720 kWh a day, whilst the kitchen has a high energy demand between 5 am and 8 pm. The laundry equipment does not operate continuously, and is switched on between 7am and 10pm. The laundry has the highest demand during the morning peak period, and the heat pumps have the highest demand during the evening peak period. A huge dip is observed in the laundry demand during the evening peak hours.

4.2.2 The site information

An on-site visit of the hotel was conducted in order to complete the information required. Furthermore information is collected through discussions with the hotel's maintenance manager, identification of existing facilities and observations. The number of existing facilities, saving measures, and the proposed retrofitting alternatives are shown in Tables 4.2 and 4.3. As observed from the afore mentioned 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 4 years. The maximum quantity of each facility type 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 in kWh and water savings in kl are estimations of 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

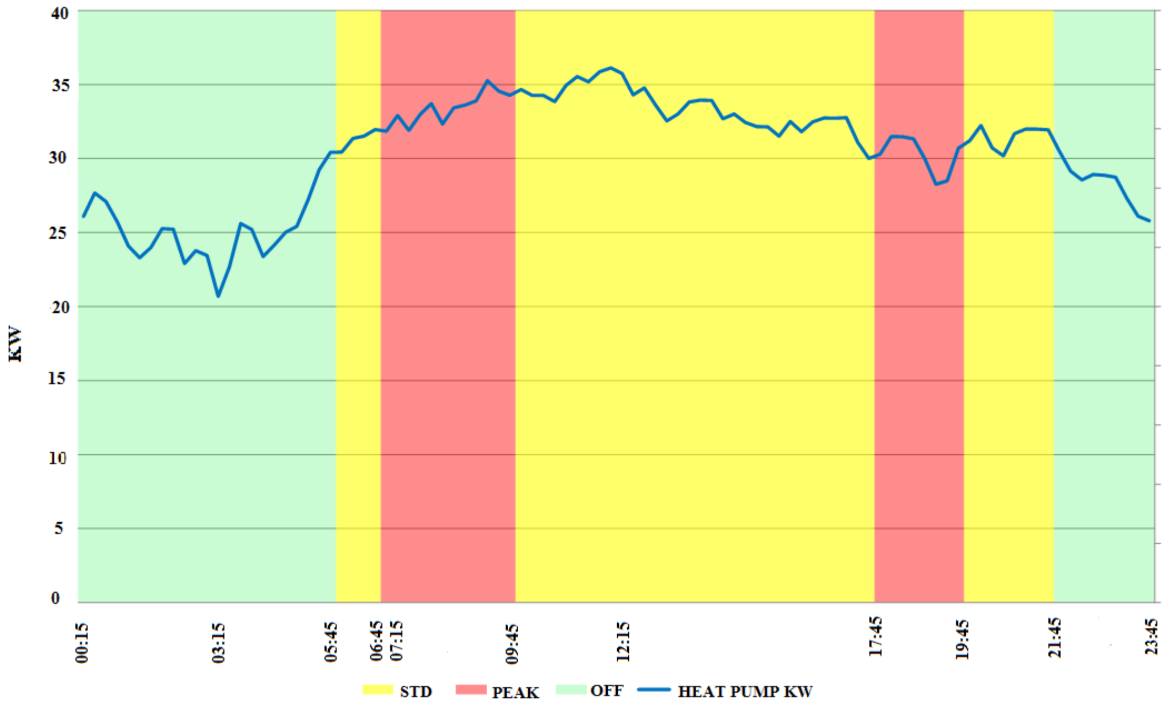

Figure 4.3: Heat pumps load profile

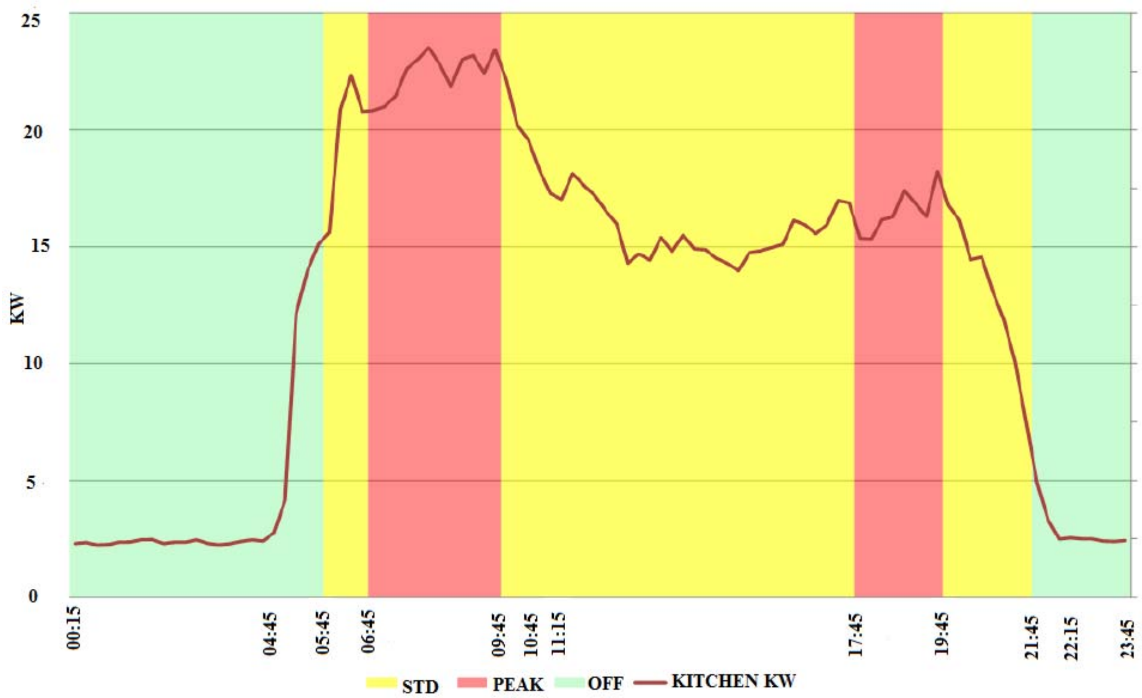

Figure 4.4: Kitchen load profile

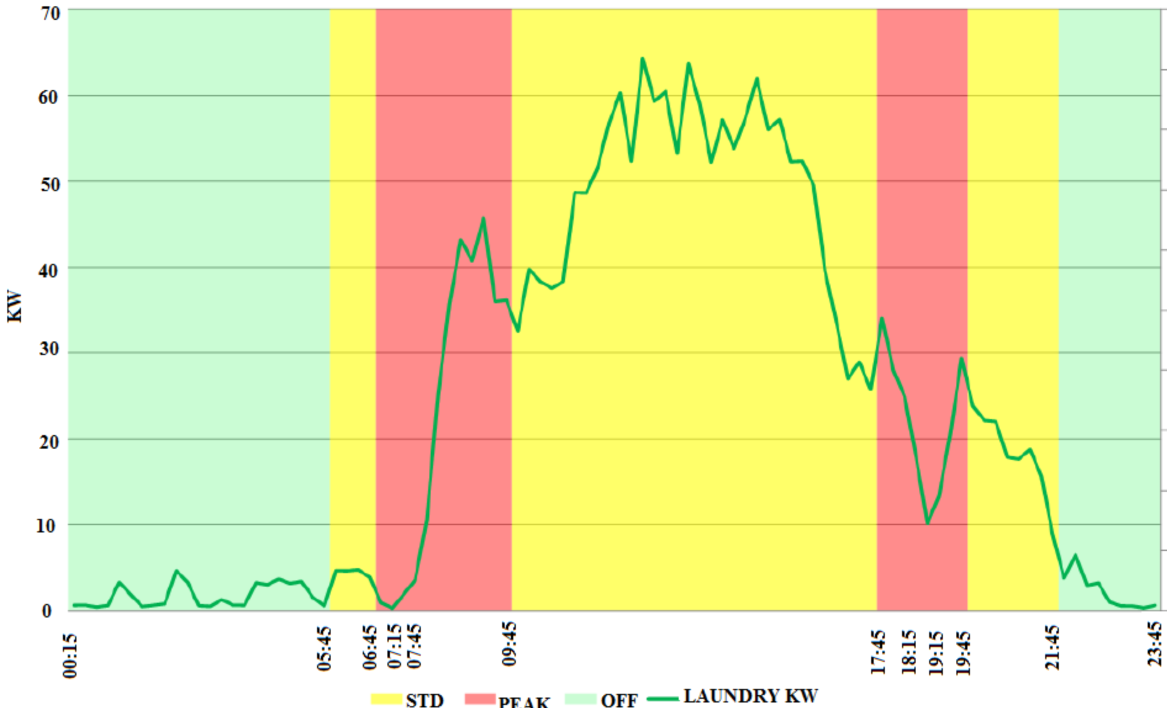

Figure 4.5: Laundering load profile

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 switched on between $2.5 - 5$ hours a day. The per unit cost for facility type i (c_i^t) and saving measure j (d_j^t) in USD (\$), is the cost of buying the proposed alternative or implementing the proposed saving measure during the first year of the retrofitting project. The prices increase yearly for the following years as a result of the 7% yearly interest rate.

It is evident from Table 4.2 that 17 different lighting fixtures were identified for the retrofitting project. The most expensive facilities to retrofit, based on the per unit cost are: the chillers ($\$147,125$) and the washing machines ($\$5,499$). The lighting fixtures are the cheapest facilities to retrofit, ranging at a unit cost of $\$8 - \$117$. The facility type with the highest quantity to be retrofitted is the shower-heads. This is as a result of the number of bedrooms in the hotel. In Table 4.2, the double pane glass for the building's entrance is the most expensive saving measure identified for implementation [2]. Though energy and water meters do not contribute to savings, they enable the hotel owner or maintenance manager to keep track of the hotel's consumption patterns. Furthermore, sub-metering is required to

[2] http://www.iaarc.org/publications/fulltext/isarc2013Paper355.pdf

achieve additional energy and water savings at no cost, by implementing behaviour changes and turning off unneeded equipment.

Table 4.2: Building retrofit input data for facilities

Facility type (i)	Existing facility	Proposed alternative	Maximum quantity z_i	Unit ES (kWh)/year	Unit WS (kl)/year	Unit cost c_i^1 ($)
1	Inncandescent 40W	LED bulb 6W (E27)	78	42	0	10
2	2-lamp 4' T8 fixture 36W	2-lamp 4' T5 28W	35	30	0	19
3	2-lamp 2' T8 fixture 18W	2-lamp 2' T5 14W	77	15	0	19
4	1-lamp 4' T8 fixture 36W	1-lamp 4' T5 28W	54	15	0	19
5	3-lamp 5' T8 fixture 58W	3-lamp 5' T5 35W	43	63	0	29
6	1-lamp 5' T8 fixture 58W	1-lamp 5' T5 35W	88	42	0	22
7	PAR 38 - 65W	CFL lamp 14W	112	93	0	35
8	3-lamp 4' T8 fixture 36W	3-lamp 4' T5 28W	25	44	0	81
9	3-lamp 4' T8 fixture 36W	3-lamp 4' T5 28W	17	44	0	27
10	2-lamp 5' T8 fixture 58W	2-lamp 5' T5 35W	23	84	0	22
11	PAR 30 - 35W	CFL lamp 7W	32	57	0	16
12	1-lamp 2' T8 fixture 18W	1-lamp 2' T5 14W	39	17	0	105
13	Incandescent 250W	LED bulb 12W	11	232	0	98
14	4-lamp 4' T8 fixture 36W	4-lamp 4' T5 28W	29	58	0	20
15	125W mercury vapor	LED flood 10W	42	105	0	8
16	Halogen 50W - 12V	LED 7W 12 V	42	78	0	8
17	Incandescent 60W	LED bulb 10W	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 shower-heads	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	147,125
28	Existing aerators	Aerator upgrade	16	0	904	66

Table 4.3: Building retrofit input data for saving measures

Saving measure type (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	55,000
2	No photovoltaic systems	Grid connected photovoltaic system	15275	0	54,000
3	Existing HVAC system	More efficient HVAC	19800	0	19,870
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

4.2.3 Case study input parameters

The building's yearly baseline energy consumption (BEC) and water consumption (BWC) are $22,409,66$ kWh and $60,534$ kl respectively. In addition, the baseline data remains constant throughout the project period (i.e. no baseline adjustments are envisaged) [46]. The electricity and water billing rate indicated is for the first year of the retrofit, the price increases yearly thereafter by an interest rate of 7%. The project period T is the time allocated to complete the retrofitting project. The project is expanded over 4 years due to limited funds, and to allow normal operations of the hotel, hence ensure that business is not affected. Furthermore, the extended project period allows contractors to work shifts that will not affect the occupants of the hotel. The yearly retrofitting budget (β_t) is strictly for retrofitting purposes, other costs such as labour and the building's energy and water service charge are not included. The lowest budget is allocated to the first year of the project in order to manage the risks from a financial perspective [47].

The LEED points for the other LEED categories (F_2^0) are determined from completed South African LEED projects in the USGBC directory [3]. 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: Certified (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.

Table 4.4: Model parameters (Case study)

Number	Parameter	Symbol	Value
1	Building annual energy consumption	BEC	$22,409,66$kWh
2	Building annual water consumption	BWC	$60,534$kl
3	Electricity billing rate	ec	0.13 $/kWh
4	Water billing rate	wc	1.48 $/kl
5	Project period	T	4 years
6	LEED points of other categories	F_2^0	45
7	Yearly project budget	$[\beta_1, \beta_2, \beta_3, \beta_4]$	$[15k, 45k, 80k, 350k]$
8	Yearly LEED point target	$[\rho_1, \rho_2, \rho_3, \rho_4]$	$[40, 50, 60, 60]$

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

4.3 CHAPTER SUMMARY

The applicability of the optimization model developed in chapter 3 is demonstrated through a case study of an existing hotel in Pretoria, the administrative capital city of South Africa. A meeting and site visit was arranged with the hotel's maintenance manager. Data regarding the existing facilities, existing measures, and operational hours is collected. Furthermore, the hotel's energy audit report is used to obtain the information related to the hotel's energy and water consumption. The model input parameters are also given in this chapter. In the chapter to follow, the results related to the case study building is presented and analyzed.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 CHAPTER OVERVIEW

The developed optimization model is applied to the case study building discussed in chapter 4. The problem is treated as a mixed integer non-linear programming problem and solved by the BONMIN optimization tool[1]. Once the optimization procedure is completed, graphs pertaining a more detailed description of the optimal selected facilities are generated. The results include (i) the number of each facility type retrofitted during each year; (ii) the retrofitting cost for each year; (iii) the building's energy and water savings for each year; (iv) the threshold and check-off point contributions as a result of the retrofit (v) the total number of LEED points achieved during each retrofitting year and (vi) the payback period for the overall project. A sensitivity analysis is performed to determine the impact of various parameters on the model.

5.2 VARYING THE FUNCTION WEIGHTING FACTORS

The optimization model has three objective functions, these are: minimizing the retrofitting cost $F_1(X)$; maximizing the LEED points $F_2(X)$, and minimizing the payback period $F_3(X)$. The objective functions are combined into one scalar function by applying a constant weight coefficient to each function ($J = w_1F_1(X) - w_2F_2(X) + w_3F_3(X)$). The weighting factor applied to each objective function can vary, and is the choice of the DM. The weight tuning method was used to determine the weighting factors that produced the most reasonable results. Furthermore, a constant value was added to change the weighting factors for every

[1]ILOG 2011, BONMIN 1.5 User's Manual

feature. The listed weighting factors are initially chosen such that only one objective function and its impact on the model is considered at a time. Table 5.1 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 energy and water savings are the savings incurred from the facilities retrofitted and the saving measures implemented. The yearly LEED points are based on the percentage energy and water savings incurred, and the saving measures implemented.

Table 5.1: Results comparison for different weighting factors

w_1	w_2	w_3	Yearly retrofitting cost ($)	Yearly energy savings(%)	Yearly water savings (%)	Yearly points	Payback period (Months)
1	0	0	[3.36k,42.5k,56.2k,0k]	[12,23,34,34]	[0,37,37,37]	[45,50,60,60]	26
0	1	0	[15k,45k,80k,235.36k]	[19,31,41,55]	[4,55,59,74]	[45,57,67,72]	29
0	0	1	[3.3k,42.5k,56.2k,0k]	[12,23,34,34]	[0,33,33,33]	[45,50,60,60]	24
0.7	0.2	0.1	[12.73k,45k,80k,0k]	[19,31,41,41]	[21,55,59,59]	[48,57,67,67]	34
0.2	0.7	0.1	[12.41k,45k,75.55k,235.32k]	[19,31,41,55]	[4,55,59,74]	[45,57,67,72]	29

When considering the cost function($w_1 = 1$, $w_2 = 0$ and, $w_3 = 0$), the yearly retrofitting cost incurred is $[3.36k, 42.5k, 56.2k, 0k]$ for each year respectively. In addition, no retrofit takes place in year 4. The energy savings percentage obtained is 12%, but this is not sufficient in order to qualify for energy savings threshold points in the first year, as the minimum energy savings percentage required is 26%. There are 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 is obtained from the second year onwards (Silver: 50 points and Gold:60 points). The payback period is 26 months.

When considering the points function ($w_1 = 0$, $w_2 = 1$ and, $w_3 = 0$), the yearly retrofitting cost incurred is $[15k, 45k, 80k, 235.36k]$ for each year respectively. The allocated funds for the first, second and third year are exhausted completely. The accumulative percentage 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 10 points more than the required points for LEED gold certification. The payback period is 29 months.

When considering the payback period function ($w_1 = 0$, $w_2 = 0$ and, $w_3 = 1$), the yearly retrofitting cost incurred is $[3.3k, 42.5k, 56.2k, 0k]$ for each year respectively. The results obtained for energy savings, water savings and LEED points, is similar to the results obtained for $w_1 = 1$, $w_2 = 0$ 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.

When all functions are considered simultaneously ($F_1(X)$, $F_2(X)$ and, $F_3(X)$), it is observed that the lowest project cost incurred is $[12.73k, 45k, 80k, 0k]$ for each year respectively, and the weighting factors are $w_1 = 0.7$, $w_2 = 0.2$ and, $w_3 = 0.1$. In addition, the facility types (x_i^1, x_i^2, x_i^3, x_i^4) and measures (y_j^1, y_j^2, y_j^3, and y_j^4) selected during each year of the retrofit, are shown in Tables 5.4 and 5.5. The washing machines is the most expensive facility retrofitted, followed by the motion activated lighting (MAL) system. The 125W mercury vapor lighting fixtures and the halogen lighting fixtures were the cheapest to retrofit. The shower heads and ironing machines were the only facilities retrofitted during the first year, and the washing machines were the only facilities during the third year. The saving measures implemented are the solar water heater system and the drip irrigation system. Furthermore, it is observed that no retrofit is done during the fourth year, resulting in a minimal cost required to maintain the LEED gold certification level during that year. This also contribute to minimizing the overall project cost. The accumulative percentage of energy savings incurred by the end of the project is 41%, and the percentage water savings incurred 59%. The LEED points achieved by the end of the project is 67. The payback period is 34 months.

The maximum LEED points of 72 is achieved when the weighting factors $w_1 = 0.2$, $w_2 = 0.7$ and, $w_3 = 0.1$ are applied. The cost incurred from the afore mentioned weighting factors is [12.41k,45k,75.55k,235.32k] for each year respectively, and the results obtained are similar to results obtained for the weighting factors $w_1 = 0$, $w_2 = 1$ and, $w_3 = 0$. The only facilities that were not retrofitted by the end of the project are the PAR 38 lamps, the chillers and one ironing machine. All the energy and water meters were implemented, and the saving measures that were implemented are the power factor correction system, the thermal pane glass at the building entrance and the toilets.

The number of facilities retrofitted and saving measures implement during each year, for the weighting factors ($w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$) and ($w_1 = 0.2, w_2 = 0.7, w_3 = 0.1$) are shown in Figs.5.1 and 5.2. For both sets of weighting factors, the facility type with the highest quantity is retrofitted during the first year of the project. The second highest quantity of facilities are retrofitted during the fourth year of the project. Furthermore, it is observed that the maximum quantity (z_i) of each facility type is retrofitted within the same year, for example: the maximum quantity of facility type 1 is retrofitted during the second year. By retrofitting the same type of facility at once, the installation cost of the project can be minimized and an optimal maintenance plan for the retrofitted facilities can be established. However, this is beyond the scope of this study and hence is not discussed here. For the weighting factors $w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$, a majority of the facilities and measures are retrofitted during the second year, and for the weighting factors $w_1 = 0.2, w_2 = 0.7, w_3 = 0.1$, a majority of the facilities and measures are retrofitted during the fourth.

The yearly percentage energy and water saving incurred for the weighting factors ($w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$) and ($w_1 = 0.2, w_2 = 0.7, w_3 = 0.1$) are shown in Figs.5.3 and 5.4. For both sets for weighting factors, it is observed that the water savings is more than the energy savings from the second year onwards. The overall energy and water savings is the highest when the weighting factors $w_1 = 0.2, w_2 = 0.7, w_3 = 0.1$ are applied.

The energy and water savings threshold point contribution, and the check off point contributions for the weighting factors ($w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$) and ($w_1 = 0.2, w_2 = 0.7, w_3 = 0.1$) are shown in Figs.5.5 and 5.6. When the weighting factors are $w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$, then the water savings threshold points are obtained for every year, and the energy savings threshold points are obtained from the second year onwards. In addition, no check-off points are obtained. When the weighting factors are $w_1 = 0.2, w_2 = 0.7, w_3 = 0.1$, then neither threshold or check-off points are obtained during the first year of retrofit, the only points available are the points obtained in the other LEED categories. The energy and water saving threshold points are obtained from the second year onwards. Furthermore, 1 check-off point is obtained for the implementation of a solar water heater system.

Table 5.2: Yearly selected facilities ($w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$)

Facility type (i)	Existing facility	Proposed alternative	Maximum quantity (z_i)	Retrofits year 1 (x_i^1)	Retrofits year 2 (x_i^2)	Retrofits year 3 (x_i^3)	Retrofits year 4 (x_i^4)	Remaining facilities
1	incandescent40W	LED Bulb 6W E27	78	0	78	0	0	0
2	2-lamp 4' T8 fixture 36W	2-lamp 4' T5 28W	35	0	0	0	0	35
3	2-lamp 2' T8 fixture 18W	2-lamp 2' T5 14W	77	0	0	0	0	77
4	1-lamp 4' T8 fixture 36W	1-lamp 4' T5 28W	54	0	0	0	0	54
5	3-lamp 5' T8 fixture 58W	3-lamp 5' T5 35W	43	0	0	0	0	43
6	1-lamp 5' T8 fixture 58W	1-lamp 5' T5 35W	88	0	0	0	0	88
7	PAR 38 - 65W	CFL lamp 14W	112	0	0	0	0	112
8	3-lamp 4' T8 fixture 36W	3-lamp 4' T5 28W	25	0	0	0	0	25
9	3-lamp 4' T8 fixture 36W	3-lamp 4' T5 28W	17	0	0	0	0	17
10	2-lamp 5' T8 fixture 58W	2-lamp 5' T5 35W	23	0	23	0	0	0
11	PAR 30 - 35W	CFL lamp 7W	32	0	32	0	0	0
12	1-lamp 2' T8 fixture 18W	1-lamp 2' T5 14W	39	0	0	0	0	39

13	Incandescent 250W	LED Bulb 12W	11	0	0	0	0	11
14	4-lamp 4' T8 fixture 36W	4-lamp 4' T5 28W	29	0	0	0	0	29
15	125W Mercury Vapor	LED Flood 10W	42	0	42	0	0	0
16	HALOGEN 50W - 12V	LED 7W 12 Volt	42	0	42	0	0	0
17	Incandescent 60W	LED Bulb 10W	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 5.3: Yearly selected measures ($w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$)

Saving measure type (j)	Existing facility	Proposed alternative	Maximum quantity	Measures year 1 (y_j^1)	Measures year 2 (y_j^2)	Measures year 3 (y_j^3)	Measures year 4 (y_j^4)	Remaining Measures
1	Poor power factor	Power-factor correction	1	0	0	0	0	1
2	No Photovoltaic Systems	Grid connected photovoltaic system	1	0	0	0	0	1
3	Existing HVAC system	More Efficient HVAC	1	0	0	0	0	1
4	No Solar water heater system installed	Installing roof mount solar water heater	1	0	1	0	0	0
5	No thermal pane glass	Double pane glass for building entrance	1	0	0	0	0	1
6	No Irrigation system	Drip Irrigation system	1	1	0	0	0	0
7	Existing toilets	Toilets replacement	1	0	0	0	0	1
8	Existing faucets	Faucets Replacement	1	0	0	0	0	1
9	Existing urinals	Urinals replacement	1	0	0	0	0	1
10	No building energy meter installed	Building energy meter	1	0	0	0	0	1
11	No energy subsystem meter installed	Metering-energy subsystem	1	0	0	0	0	1
12	No building water meter installed	Building water meter	1	0	0	0	0	1
13	No building water subsystem meter	Metering-water subsystem	1	0	0	0	0	1

Table 5.4: Yearly selected facilities ($w_1 = 0.2, w_2 = 0.7, w_3 = 0.1$)

Facility type (i)	Existing facility	Proposed alternative	Maximum quantity (z_i)	Retrofits year 1 (x_i^1)	Retrofits year 2 (x_i^2)	Retrofits year 3 (x_i^3)	Retrofits year 4 (x_i^4)	Remaining facilities
1	incandescent40W	LED Bulb 6W (Candle dimmable) E27	78	0	78	0	0	0
2	2-lamp 4’ T8 fixture 36W	2-lamp 4’ T5 28W	35	0	0	0	35	0
3	2-lamp 2’ T8 fixture 18W	2-lamp 2’ T5 14W	77	0	0	0	77	0
4	1-lamp 4’ T8 fixture 36W	1-lamp 4’ T5 28W	54	0	0	0	54	0
5	3-lamp 5’ T8 fixture 58W	3-lamp 5’ T5 35W	43	0	0	0	43	0
6	1-lamp 5’ T8 fixture 58W	1-lamp 5’ T5 35W	88	0	0	0	88	0
7	PAR 38 - 65W	CFL lamp 14W	112	0	0	0	112	0
8	3-lamp 4’ T8 fixture 36W	3-lamp 4’ T5 28W	25	0	0	0	0	25
9	3-lamp 4’ T8 fixture 36W	3-lamp 4’ T5 28W	17	0	0	0	17	0
10	2-lamp 5’ T8 fixture 58W	2-lamp 5’ T5 35W	23	0	23	0	0	0
11	PAR 30 - 35W	CFL lamp 7W	32	0	32	0	0	0

12	1-lamp 2' T8 fixture 18W	1-lamp 2' T5 14W	39	0	0	0	33	6
13	Incandescent 250W	LED Bulb 12W	11	0	0	0	11	0
14	4-lamp 4' T8 fixture 36W	4-lamp 4' T5 28W	29	0	0	0	29	0
15	125W Mercury Vapor	LED Flood 10W	42	0	42	0	0	0
16	HALOGEN 50W - 12V	LED 7W 12 Volt	42	0	42	0	0	0
17	Incandescent 60W	LED Bulb 10W (Non dimmable)	41	0	0	0	41	0
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	3	0
21	High flow showerheads	Low-flow showerheads	230	230	0	0	0	0
22	Existing washing machines	Energy Saving Washing machines	25	0	1	12	11	1
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	15	0
26	Existing Vending Machine	Energy Saving Vending machine	2	0	0	0	2	0
27	Old chillers	New chillers	2	0	0	0	0	2
28	Existing Aerators	Aerator upgrade	16	0	16	0	0	0

Table 5.5: Yearly selected measures ($w_1 = 0.2, w_2 = 0.7, w_3 = 0.1$)

Saving measure type (j)	Existing facility	Proposed alternative	Maximum quantity	Measures year 1 (y_j^1)	Measures year 2 (y_j^2)	Measures year 3 (y_j^3)	Measures year 4 (y_j^4)	Remaining Measures
1	Poor power factor	Power-factor correction	1	0	0	0	1	0
2	No Photovoltaic Systems	Grid connected photovoltaic system	1	0	0	0	0	1
3	Existing HVAC system	More Efficient HVAC	1	0	0	0	1	0
4	No Solar water heater system installed	Installing roof mount solar water heater	1	0	1	0	0	0
5	No thermal pane glass	Double pane glass for building entrance	1	0	0	0	0	1
6	No Irrigation system	Drip Irrigation system	1	0	1	0	0	0
7	Existing toilets	Toilets replacement	1	0	0	0	1	0
8	Existing faucets	Faucets Replacement	1	0	0	0	0	1
9	Existing urinals	Urinals replacement	1	0	0	0	1	0
10	No building energy meter installed	Building energy meter	1	0	0	0	0	1
11	No energy subsystem meter installed	Metering-energy subsystem	1	0	0	0	0	1
12	No building water meter installed	Building water meter	1	0	0	0	0	1
13	No building water subsystem meter	Metering-water subsystem	1	0	0	0	0	1

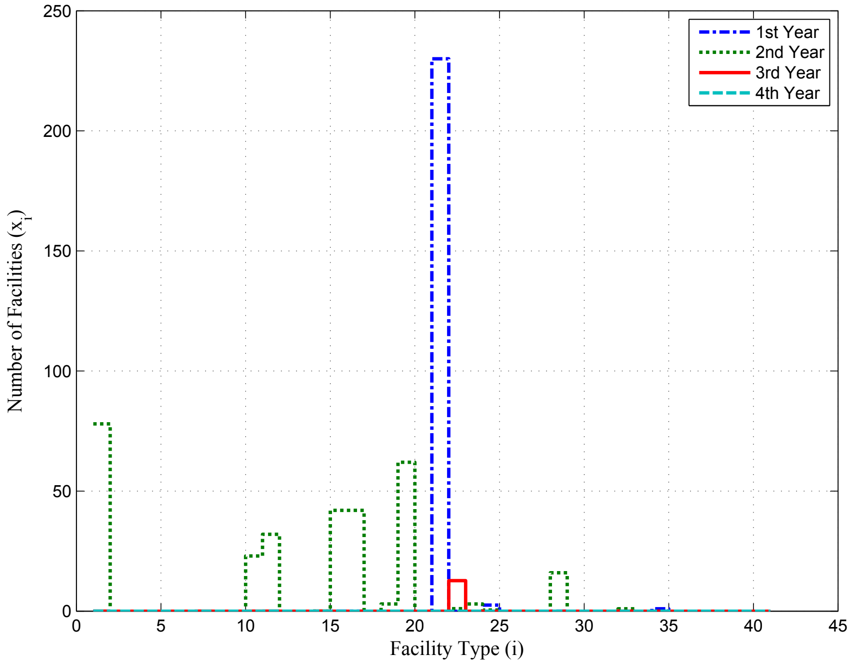

Figure 5.1: Yearly selected facilities and measures ($w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$)

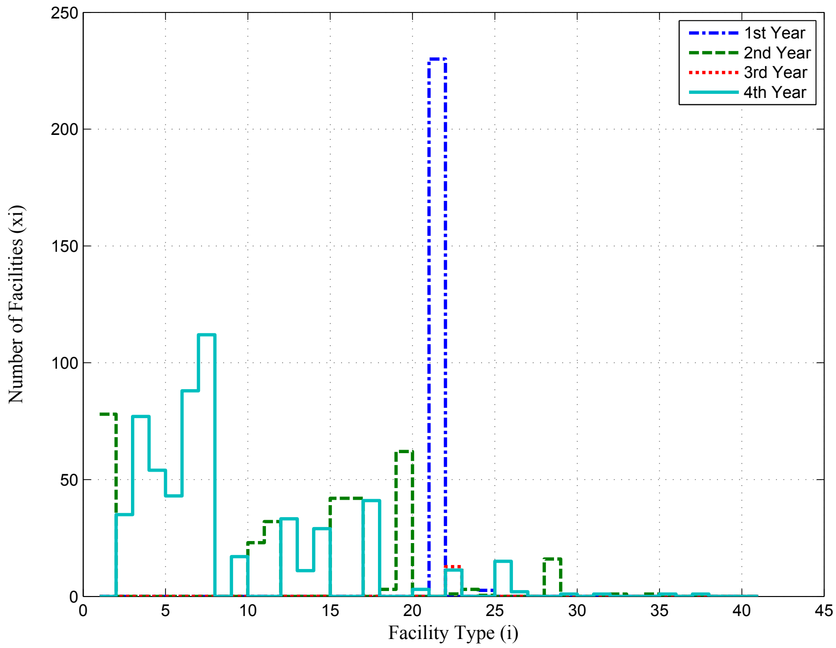

Figure 5.2: Yearly selected facilities and measures ($w_1 = 0.2, w_2 = 0.7, w_3 = 0.1$)

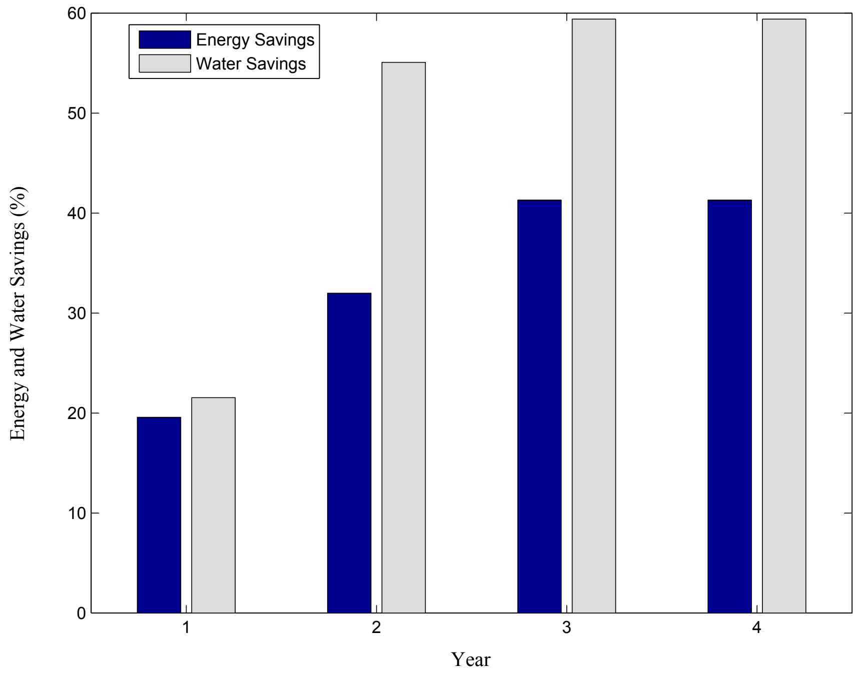

Figure 5.3: Building energy and water savings ($w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$)

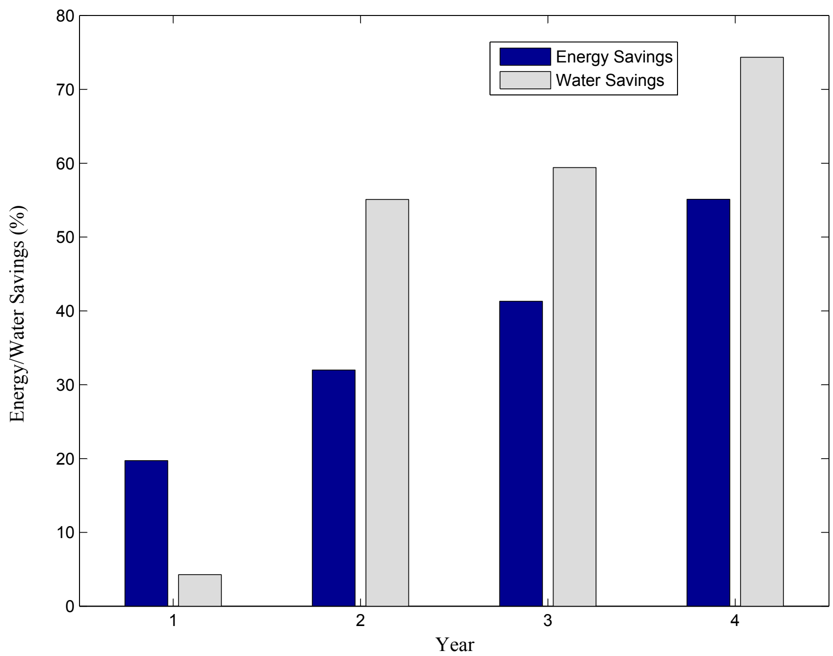

Figure 5.4: Building energy and water savings ($w_1 = 0.2, w_2 = 0.7, w_3 = 0.1$)

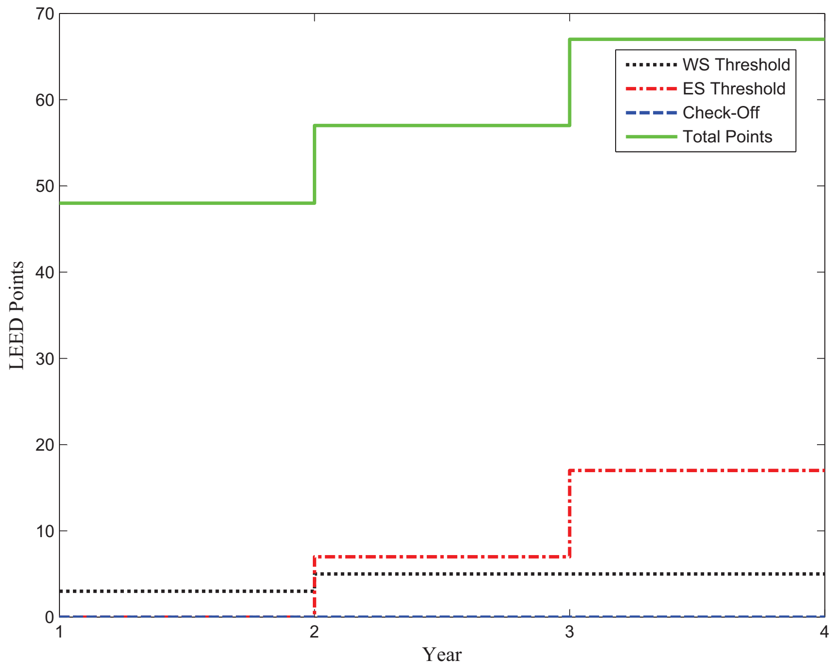

Figure 5.5: Threshold and check-off point contributions ($w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$)

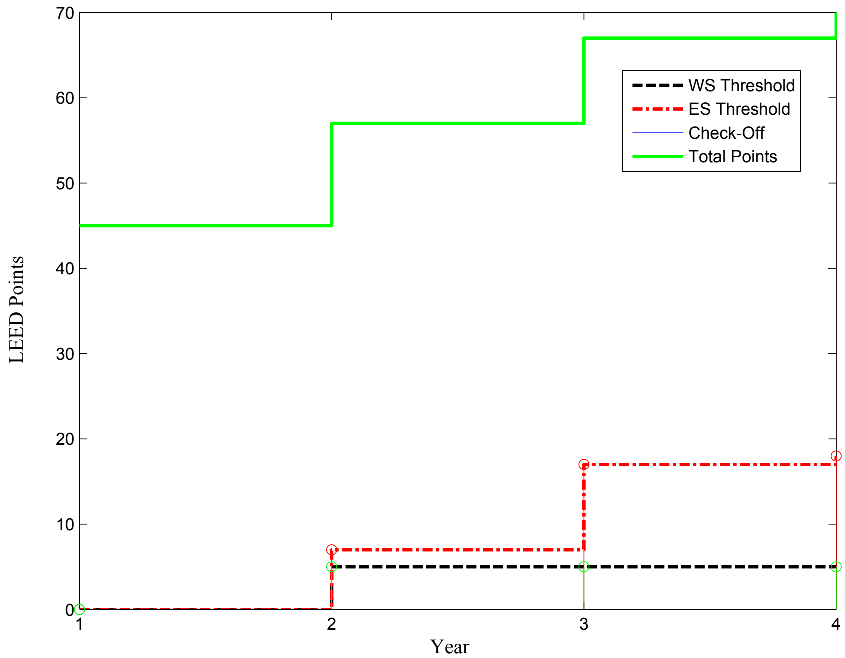

Figure 5.6: Threshold and check-off point contributions ($w_1 = 0.2, w_2 = 0.7, w_3 = 0.1$)

5.3 VARYING THE BUDGET

The DM may wish to retrofit all the existing facilities and measures identified by the end of the project. Hence, the cost associated with such a project must be identified. The optimization model is implemented with the weighting factors ($w_1 = 0.2, w_2 = 0.7, w_3 = 0.1$), whilst the yearly allocated budget varies. Table 5.6 shows the results obtained for two different sets of retrofitting budgets.

Table 5.6: Results comparison for different budgets

β_1 ($)	β_2 ($)	β_3 ($)	β_4 ($)	Yearly retrofitting cost ($)	Yearly energy savings(%)	Yearly water savings (%)	Yearly points	Payback period (Months)
350k	550k	750k	1m	[0,406.7k ,188.3k,77.9k]	[0,56,57,57]	[0,76,76,76]	[45,72,70,80]	60
350k	80k	45k	15k	[145.3k,80k,0k,0k]	[39,51.7,51.7,51.7]	[9,70,70,70]	[60,68,68,68]	60

When the retrofitting budget is [350k , 550k, 750k, 1m] for each year respectively, the lowest retrofitting cost of $77.9k is incurred during the fourth year, and the highest cost of $406.7k is incurred during the second year. There were no retrofits done during the first year, hence, no energy and water savings are obtained. In addition, from the second year on wards, the total percentage of energy saved is above 50%, and the total percentage of water saved is above 70%. The LEED gold certification level is achieved during the second and third year (72 and 70 points are obtained respectively), whilst the platinum certification level (80 points are obtained) is achieved during the fourth year. The project payback period is 60 months. In Tables 5.7 and 5.8 the selected number of facilities and measures during each year of the retrofit are shown. As indicated, no facilities are retrofitted during the first year, and all the facilities except for the chillers are retrofitted during the second year. The only facility that was not retrofitted by the end of the project is the remaining chiller. When referring to Table 5.8, it is observed that no saving measures are implemented during the first and the third year. All the saving measures were implemented by the end of the project. The facilities and measures selected, energy and water saving incurred, and the LEED point contributions are shown in Figs.5.7, 5.8, and 5.9. It is observed that most of the facilities are retrofitted during the second year, furthermore, the energy and water savings remained constant from the second year on wards, and the energy savings threshold points contributed the most to the LEED points obtained.

When the retrofitting budget is [350k , 80k, 45k, 15k] for each year respectively, the lowest retrofitting cost of \$80k is incurred during the second year, and the highest cost of \$145.3k is incurred during the first year. There were no retrofits done during the third and fourth year, hence, no additional energy and water savings are obtained. In addition, the total percentage of energy savings incurred during the first year is 39%, and from the second year on wards is 51.7%. The total percentage of water saved is 9% for the first year, and 70% for the second year on wards. The LEED gold certification level is obtained for each retrofitting year. The project payback period is 60 months.

Table 5.7: Yearly selected facilities ($[\beta_1, \beta_2, \beta_3, \beta_4] = [350k, 550k, 750k, 1m]$)

Facility type (i)	Existing facility	Proposed alternative	Maximum quantity (z_i)	Retrofits year 1 (x_i^1)	Retrofits year 2 (x_i^2)	Retrofits year 3 (x_i^3)	Retrofits year 4 (x_i^4)	Remaining facilities
1	incandescent40W	LED Bulb 6W (Candle dimmable) E27	78	0	78	0	0	0
2	2-lamp 4' T8 fixture 36W	2-lamp 4' T5 28W	35	0	35	0	0	0
3	2-lamp 2' T8 fixture 18W	2-lamp 2' T5 14W	77	0	77	0	0	0
4	1-lamp 4' T8 fixture 36W	1-lamp 4' T5 28W	54	0	54	0	0	0
5	3-lamp 5' T8 fixture 58W	3-lamp 5' T5 35W	43	0	43	0	0	0
6	1-lamp 5' T8 fixture 58W	1-lamp 5' T5 35W	88	0	88	0	0	0
7	PAR 38 - 65W	CFL lamp 14W	112	0	112	0	0	0
8	3-lamp 4' T8 fixture 36W	3-lamp 4' T5 28W	25	0	25	0	0	0
9	3-lamp 4' T8 fixture 36W	3-lamp 4' T5 28W	17	0	17	0	0	0
10	2-lamp 5' T8 fixture 58W	2-lamp 5' T5 35W	23	0	23	0	0	0
11	PAR 30 - 35W	CFL lamp 7W	32	0	32	0	0	0

12	1-lamp 2' T8 fixture 18W	1-lamp 2' T5 14W	39	0	39	0	0	0
13	Incandescent 250W	LED Bulb 12W	11	0	11	0	0	0
14	4-lamp 4' T8 fixture 36W	4-lamp 4' T5 28W	29	0	29	0	0	0
15	125W Mercury Vapor	LED Flood 10W	42	0	42	0	0	0
16	HALOGEN 50W - 12V	LED 7W 12 Volt	42	0	42	0	0	0
17	Incandescent 60W	LED Bulb 10W (Non dimmable)	41	0	41	0	0	0
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	3	0	0	0
21	High flow showerheads	Low-flow showerheads	230	0	230	0	0	0
22	Existing washing machines	Energy Saving Washing machines	25	0	25	0	0	0
23	Existing Dryers	Energy efficient dryers	3	0	3	0	0	0
24	Existing Ironing Machines	Energy Efficient Ironing Machine	3	0	3	0	0	0
25	Pool pump	Eco pump	15	0	15	0	0	0
26	Existing Vending Machine	Energy Saving Vending machine	2	0	2	0	0	0
27	Old chillers	New chillers	2	0	0	1	0	1
28	Existing Aerators	Aerator upgrade	16	0	16	0	0	0

Table 5.8: Yearly selected measures ($[\beta_1, \beta_2, \beta_3, \beta_4] = [350k, 550k, 750k, 1m]$)

Saving measure type (j)	Existing facility	Proposed alternative	Maximum quantity	Measures year 1 (y_j^1)	Measures year 2 (y_j^2)	Measures year 3 (y_j^3)	Measures year 4 (y_j^4)	Remaining Measures
1	Poor power factor	Power-factor correction	1	0	1	0	0	0
2	No Photovoltaic Systems	Grid connected photovoltaic system	1	0	1	0	0	0
3	Existing HVAC system	More Efficient HVAC	1	0	1	0	0	0
4	No Solar water heater system installed	Installing roof mount solar water heater	1	0	1	0	0	0
5	No thermal pane glass	Double pane glass for building entrance	1	0	0	0	1	0
6	No Irrigation system	Drip Irrigation system	1	0	1	0	0	0
7	Existing toilets	Toilets replacement	1	0	1	0	0	0
8	Existing faucets	Faucets Replacement	1	0	1	0	0	0
9	Existing urinals	Urinals replacement	1	0	1	0	0	0
10	No building energy meter installed	Building energy meter	1	0	0	0	1	0
11	No energy subsystem meter installed	Metering-energy subsystem	1	0	0	0	1	0
12	No building water meter installed	Building water meter	1	0	0	0	1	0
13	No building water subsystem meter	Metering-water subsystem	1	0	0	0	1	0

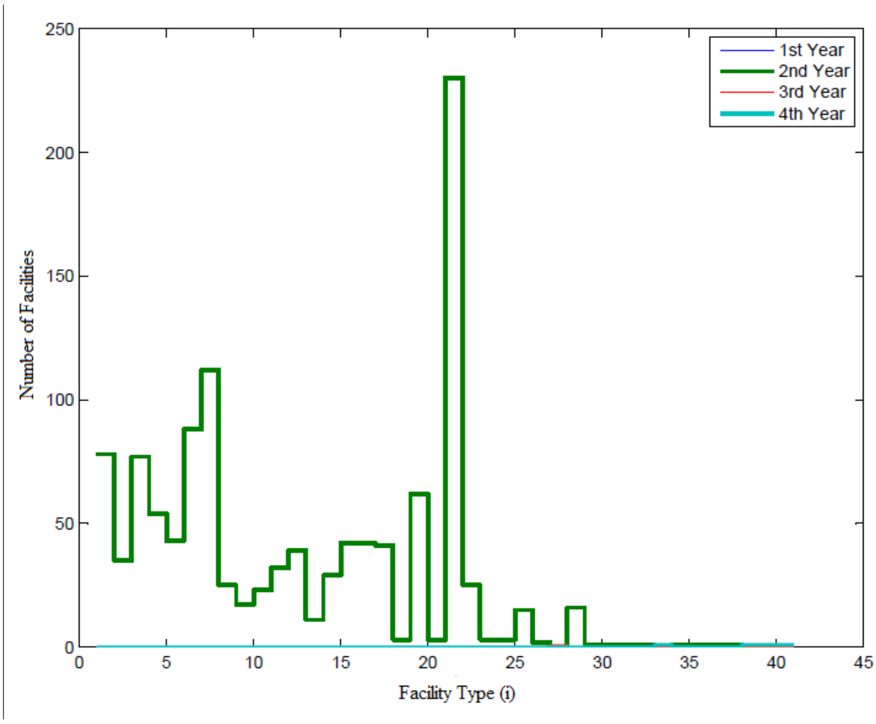

Figure 5.7: Yearly selected facilities and measures ($[\beta_1, \beta_2, \beta_3, \beta_4] = [350k, 550k, 750k, 1m]$)

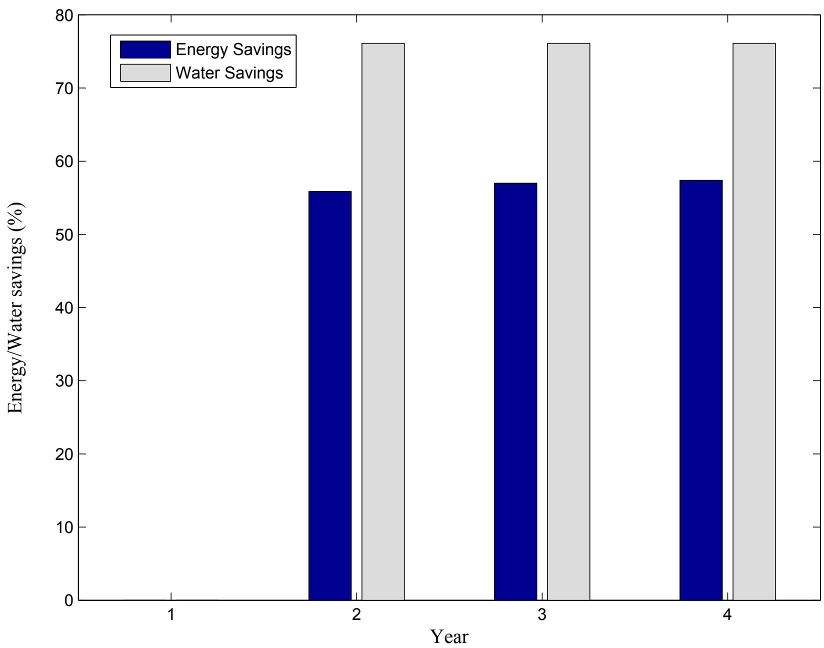

Figure 5.8: Energy and water savings ($[\beta_1, \beta_2, \beta_3, \beta_4] = [350k, 550k, 750k, 1m]$)

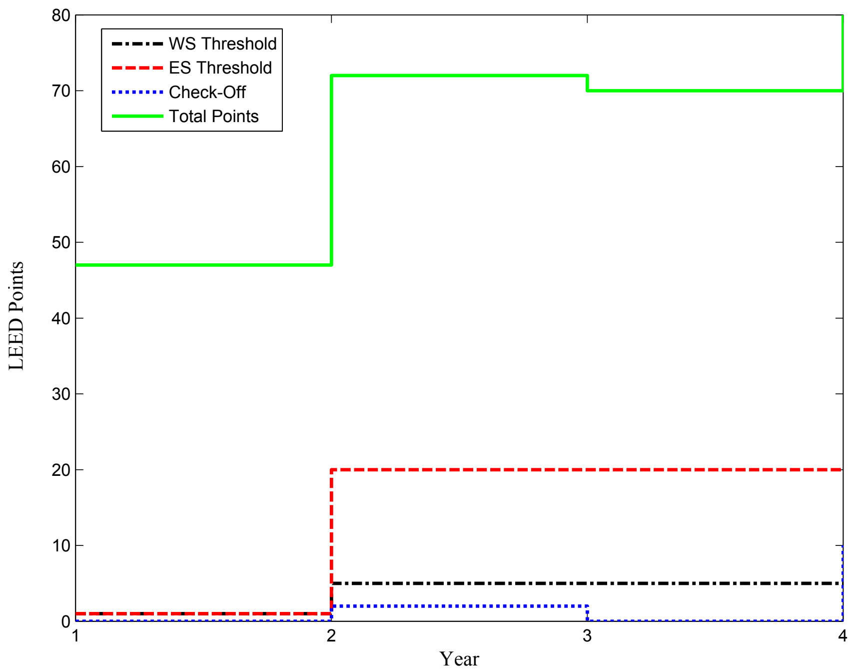

Figure 5.9: LEED point contributions ($[\beta_1, \beta_2, \beta_3, \beta_4] = [350k, 550k, 750k, 1m]$)

5.4 DISCUSSION: RETROFITS AND GREEN BUILDING CERTIFICATION

The first research question addressed in this study is whether or not building retrofits can be implemented with the intend of green building certification. The research study revealed that 50% of the points under the LEED-EB standards come from the energy and water efficiency categories. Furthermore, it was found that both threshold and check-off points can be obtained. The retrofitting of existing facilities, the installation of renewable energy and water systems, and the implementation of energy and water saving measures can be considered as retrofitting options. This will ensure that both energy and water saving threshold points are obtained, whilst also ensuring that check-off points are obtained. Most of the points from the aforementioned categories are assigned based on the total percentage of energy and water saved. Hence, by replacing inefficient facilities with efficient ones, the energy and water savings are maximized and as a result the energy and water saving threshold points are maximized. Green building certification for existing buildings can thus be achieved through retrofitting.

5.5 DISCUSSION: IMPACT OF WEIGHTING FACTORS

The second research question addressed in this study is whether or not the weighting factors assigned to each objective function has an impact on the model. The results show that when the weighting factors ($w_1 = 1$, $w_2 = 0$ and, $w_3 = 0$) are applied, only the minimization of the retrofitting cost is considered. The results revealed that the optimally selected facilities and measures were those facilities and measure that result in the minimum LEED point target being obtained (Certified:40, Silver: 50 points, and Gold:60 points).

When the weighting factors ($w_1 = 0$, $w_2 = 1$ and, $w_3 = 0$) are applied, only the maximization of points is considered. The maximum number of energy saving threshold points (20 points), and maximum water savings threshold points (5 points) are achieved by the fourth year of the project. When the weighting factors ($w_1 = 0$, $w_2 = 0$ and, $w_3 = 1$) are assigned to the model, only the minimization of the payback period is considered. It is noted that facilities and measures were selected such that the model constraints are met. The LEED points obtained are the minimum required for each certification level.

The optimization model objectives are to minimize cost, maximize points, and minimize the payback period simultaneously. Hence, the objective functions must be considered simultaneously by applying a non-zero weighting factor to each objective function. The final weighting factors chosen for this research study are $w_1 = 0.7$, $w_2 = 0.2$ and, $w_3 = 0.1$. The retrofitting cost incurred for each year respectively is $[12.73k, 45k, 80k, 0k]$, the LEED points obtained for each year respectively is $[48, 57, 67, 67]$, and the payback period is 34 months.

5.6 DISCUSSION: OPTIMAL FACILITIES AND SAVING MEASURES

The third research question addressed in this study is whether there is a correlation between the number and type of selected facilities and measures. As observed from Tables 4.2 and 4.3, there is a maximum number, cost, energy savings and water savings associated with each facility type and measure. Based on the results obtained for the weighting factors $w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$ (Tables 5.4 and 5.5), it is observed that the model facilities were chosen based on the model constraints: the budget; LEED point target and maximum number of each facility type available for retrofit. Furthermore, it is observed that the maximum quantity (z_i) of each facility type is retrofitted within the same year, for example, the maximum quantity of facility type 1 is retrofitted during the second year. By retrofitting the same type of facility at once, the installation cost of the project can be minimized and an optimal maintenance plan for the retrofitted facilities can be established. However, this is beyond the scope of this study and hence, is not discussed here.

5.7 SENSITIVITY ANALYSIS

By varying the weighting factors, and by assigning different retrofitting budgets, the robustness of the model is evaluated. With reference to the results obtained in sections 5.2 and 5.3, it is observed that the weighting factors have the greatest impact on the results. For example, when the weighting factors ($w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$) are applied, the facilities and measures are chosen such that the minimization of retrofitting is prioritized. When the weighting factors ($w_1 = 0.2, w_2 = 0.7, w_3 = 0.1$) are applied, the facilities are chosen such that the maximization of LEED points are prioritized first, and the minimization of retrofitting cost prioritized second. The sensitivity analysis proves that the model is robust.

5.8 CHAPTER SUMMARY

The developed model results are presented and discussed. Two different scenarios are considered: when the function weighting factors vary and when the allocated budget vary. The selected facilities, retrofitting cost, energy savings, water savings, and LEED points obtained are analyzed for both scenarios. The robustness of the model is also analyzed. This study extends previous models developed for existing building retrofits by incorporating LEED green building certification. By retrofitting facilities in both the energy and water efficiency categories, sufficient points can be obtained in order to qualify for energy saving threshold points, water saving threshold points and check-off points. The function weighting factors have the greatest impact on the model results. Hence, the retrofitting facilities and measures are chosen based on precedence (the function with the highest weighting factor is prioritized). After the consideration of a wide range of weighting factors, the chosen weighting factors are $w_1 = 0.7$, $w_2 = 0.2$, and $w_3 = 0.1$. The trend of the selected facilities and measures is affected by the model constraints. In addition, the facilities and measures were selected such that the maximum quantity of each facility is retrofitted within the same year.

CHAPTER 6

CONCLUSION

The growing popularity of green buildings has led to a search for methods to incorporate green building certification in existing building retrofits. This study presented a multi-objective optimization model for existing building retrofits. The objectives of the model are to minimize cost, maximize LEED points, and to minimize the payback period. The LEED-EB standards were used as a reference to identify the facilities to retrofit and measures to implement, and hence, qualify for LEED certification. It was found that the EA and WE categories of LEED contribute up to 50% of the total points available. Therefore, facilities and measures related to these two categories were identified as retrofitting options. The retrofitting project is implemented over a period of 4 years, and the model constraints were the maximum number of each facility type available for retrofit, the budget assigned to each year of the retrofit, and the LEED point target for each year of the retrofit. The problem is treated as a MINL programming problem, and solved in MATLAB by the BONMIN optimization tool.

The function weighting factors used were $w_1 = 0.7$, $w_2 = 0.2$ and, $w_3 = 0.1$, and a summary of the corresponding results is shown in Table6.1. The building's energy and water savings, LEED points obtained and the investment for the overall retrofitting period is considered. The retrofitting budgets are the funds allocated to the project. The retrofitting cost is the investment required in order to retrofit or implement the selected facilities and measures. For the case studied, 28% of the allocated budget was utilized for the overall project. In addition, the maximum available funds for the second and third year, was utilized fully. The remaining funds from the first and fourth year can be used to retrofit facilities which were not selected by the model. The percentage energy and water savings are the ratios of the energy and water savings compared to the the building's baseline energy and water consumption that is indicated in Table 4.1. Furthermore, the building's yearly energy and water savings are shown in Fig.5.3 where it is evident that the percentage energy and water savings increases for each consecutive year. The overall energy and water savings are the savings achieved at the end of the last year of retrofit as the savings are assumed to persist. The cost benefit is the profit obtained as a result of the energy and water savings. The assumption is made that retrofitting is done at the beginning of each year. The discounted payback period obtained by the end of the project is 34 months, which is low 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. The LEED platinum certification level was not considered for this study as it is more applicable to LEED-NC (new construction of buildings).

Table 6.1: Building Performance and Economic Indicators ($w_1 = 0.7, w_2 = 0.2, w_3 = 0.1$)

Performance indicator	Year 1	Year 2	Year 3	Year 4	Total
Retrofitting Budget($)	15k	45k	80k	350k	490k
Retrofitting Cost ($)	12.73k	45k	80K	0k	137.73k
Energy Savings (%)	19	31	41	41	41
Water Savings (%)	21	55	59	59	59
Cost Benefit ($)	71.97k	142.82k	176.33k	176.33k	176.33k
LEED Points	48	57	67	67	67

The following conclusions are made from the final results of this study:

- Green building standards, in particular LEED-EB, can be used as a reference for existing building retrofits if the intend is to obtain green building certification
- Green building certification is not obtained through the retrofit, but can be obtained once the requirements for LEED EB are met according to the standard guidelines.
- The overall cost associated with such a retrofitting project is between $\$13k - 140k$ for each year respectively.

- By implementing the retrofitting project over several years, the cost benefits from the preceding year may reduce the required funds for the overall project. Therefore, a shorter payback period can be achieved.

- The LEED green building certification up to the gold level can be achieved for such a retrofitting project.

6.1 FUTURE RECOMMENDATIONS

For existing buildings, validations from operation data after retrofitting are recommended over simulation results from eQUEST[1]. Through an energy simulation tool, the impact of the building's structure on the energy savings can be further evaluated, in particular for old buildings. The cost benefit from carbon tax is not evaluated in this study, this can also be incorporated in future work.

Finally, this model considered retrofitting in only two LEED categories. Future models can be expanded to include retrofitting opportunities in the remaining categories of LEED.

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