

**OPTIMAL ENERGY-EFFICIENCY RETROFIT AND MAINTENANCE PLANNING FOR  
EXISTING BUILDINGS CONSIDERING GREEN BUILDING POLICY COMPLIANCE**

by

**Yuling Fan**

Submitted in partial fulfillment of the requirements for the degree  
Philosophiae Doctor (Electrical Engineering)

in the

Department of Electrical, Electronic and Computer Engineering  
Faculty of Engineering, Built Environment and Information Technology

UNIVERSITY OF PRETORIA

September 2017

## SUMMARY

---

### **OPTIMAL ENERGY-EFFICIENCY RETROFIT AND MAINTENANCE PLANNING FOR EXISTING BUILDINGS CONSIDERING GREEN BUILDING POLICY COMPLIANCE**

by

**Yuling Fan**

Promoter(s): Prof. Xiaohua Xia  
Department: Electrical, Electronic and Computer Engineering  
University: University of Pretoria  
Degree: Philosophiae Doctor (Electrical Engineering)  
Keywords: Building energy efficiency, retrofit planning, rooftop PV system, energy performance certificate, green building compliance, economic analysis, multi-objective optimization, maintenance planning.

Reducing global energy consumption is a common challenge faced by the human race due to the energy shortage and growing energy demands. The building sector bears a large responsibility for the total energy consumption throughout the world. In particular, it was concluded that existing buildings, which are usually old and energy-inefficient, are the main reason for the high energy consumption of the building sector, in view of the low replacement rate (about 1%-3% per year) of existing buildings by new energy-efficient buildings. Therefore, improving the energy efficiency of existing buildings is a feasible and effective way to reduce energy consumption and mitigate the environmental impact of the building sector.

The high energy intensity and requirements of a green building policy are the main motivation of this study, which focuses on finding cost-effective solutions to green building retrofit and maintenance planning to reduce energy consumption and ensure policy compliance.

As about 50% of the total energy usage of a general building is caused by its envelope system, this study first proposes a multi-objective optimization approach for building envelope retrofit planning in

Chapter 2. The purpose is to maximize the energy savings and economic benefits of an investment by improving the energy efficiency of existing buildings with the optimal retrofit plans obtained from the proposed approach. In the model formulation, important indicators for decision makers to evaluate an investment, including energy savings, net present value and the payback period, are taken into consideration. In addition, a photovoltaic (PV) power supply system is considered to reduce the energy demand of buildings because of the adequate solar resource in South Africa. The performance degradation of the PV system and corresponding maintenance cost are built into the optimization process for an accurate estimation of the energy savings and payback period of the investment so that decision makers are able to make informed decisions. The proposed model also gives decision makers a convenient way to interact with the optimization process to obtain a desired optimal retrofit plan according to their preferences over different objectives.

In addition to the envelope system, the indoor systems of a general building also account for a large proportion of the total energy demand of a building. In the literature, research related to building retrofit planning methods aiming at saving energy examines either the indoor appliances or the envelope components. No study on systematic retrofit plan for the whole building, including both the envelope system and the indoor systems, has been reported so far. In addition, a systematic whole-building retrofit plan taking into account the green building policy, which in South Africa is the energy performance certificate (EPC) rating system, is urgently needed to help decision makers to ensure that the retrofit is financially beneficial and the resulting building complies with the green building policy requirements. This has not been investigated in the literature. Therefore, Chapter 4 of this thesis fills the above-mentioned gaps and presents a model that can determine an optimal retrofit plan for the whole building, considering both the envelope system and indoor systems, aiming at maximizing energy savings in the most cost-effective way and achieving a good rating from the EPC rating system to comply with the green building policy in South Africa. As reaching the best energy level from the EPC rating system for a building usually requires a high amount of investment, resulting in a long payback period, which is not attractive for decision makers in view of the vulnerable economic situation of South Africa, the proposed model treats the retrofit plan as a multi-year project, improving efficiency targets in consecutive years. That is to say, the model breaks down the once-off long-term project into smaller projects over multiple financial years with shorter payback periods. In that way, the financial concerns of the investors are alleviated. In addition, a tax incentive program to encourage energy saving investments in South Africa is considered in the optimization problem to explore the economic benefits of the retrofit projects fully.

Considering both the envelope system and indoor systems, many systems and items that can be retrofitted and massive retrofit options available for them result in a large number of discrete decision variables for the optimization problem. The inherent non-linearity and multi-objective nature of the optimization problem and other factors such as the requirements of the EPC system make it difficult to solve the building retrofit problem. The complexity of the problem is further increased when the target buildings have many floors. In addition, there is a large number of parameters that need to be obtained in the building retrofit optimization problem. This requires a detailed energy audit of the buildings to be retrofitted, which is an expensive bottom-up modeling exercise. To address these challenges, two simplified methods to reduce the complexity of finding the optimal whole-building retrofit plans are proposed in Chapter 4.

Lastly, an optimal maintenance planning strategy is presented in Chapter 5 to ensure the sustainability of the retrofit. It is natural that the performance of all the retrofitted items will degrade over time and consequently the energy savings achieved by the retrofit will diminish. The maintenance plan is therefore studied to restore the energy performance of the buildings after retrofit in a cost-effective way. Maintenance planning for the indoor systems is not considered in this study because it has been thoroughly investigated in the literature. In addition, a maintenance plan for the PV system involved in the retrofit of this study is investigated in Chapter 2.

Chapter 6 concludes all the findings of this thesis and puts forward some topics for possible future research.

## ACKNOWLEDGMENT

I first would like to express my sincere gratitude to my supervisor, Prof. Xiaohua Xia, for his constant encouragement and guidance. In the past years, Prof. Xia not only guided me on working as a researcher, but also assisted and supported me in many aspects of my life. Thanks to him, I am honored to be a member of the Measurement and Verification team at the University of Pretoria, which is contracted by Eskom, the largest utility company in South Africa. This offers me an opportunity of being more mature and doing better at getting along with people. In addition, his rigorous scientific attitude, meticulous attitude and genial personality deeply inspired me. Thanks to him, I am able to finish my thesis.

I would also like to express my gratefulness to my friends in South Africa, including Dr Xianming Ye and his family, Dr Donghui Wei and his family, Nan Wang and his family, Ming Zhang, Dr Bo Wang, Dr Xueliang Cai's family, Dr Zhou Wu, Dr Bing Zhu, Shi Wang, Jun Mei, and others. I Thank them for their kindness, support and company in the years we spent together. I felt at home in South Africa because of them.

Lastly, I want to thank my brother for his unwavering love. He always gives me the strongest support, no matter where I am and what decisions I have made. I would also like to express my heartfelt gratitude to my husband, Lijun Zhang, for his understanding, support, caring and selfless love during the days we have been together. He is the man who made my life happy and meaningful in many ways. My brother and husband are the most important persons in my life. I hope I can bring them more happiness and joy in future.

Yuling Fan

University of Pretoria, South Africa

September 2017

## PUBLICATIONS

### PUBLICATIONS RELEVANT TO THIS THESIS

[J1] Y. Fan and X. Xia, “A multi-objective optimization model for energy-efficiency building envelope retrofitting plan with rooftop PV system installation and maintenance,” *Applied Energy*, vol. 189, pp. 327–335, 2017.

[J2] Y. Fan and X. Xia, “Energy-efficiency building retrofit planning for green building compliance,” *Building and Environment*, submitted, 2017.

[J3] Y. Fan and X. Xia, “Building retrofit optimization models using notch test data considering energy performance certificate compliance,” *Energy*, submitted, 2017.

[C1] Y. Fan and X. Xia, “An optimization model for building envelope retrofit considering energy performance certificate,” in *Chinese Control Conference, 2017*, Dalian, China, 2017.

[C2] Y. Fan and X. Xia, “A building retrofit optimization model using notch test data,” in *Control Conference Africa*, Johannesburg, South Africa, December 2017.

[C3] Y. Fan and X. Xia, “An optimal maintenance plan for building envelope insulation materials after retrofitting,” in *Chinese Automation Congress*, Wuhan, China, November 2015.

[C4] Y. Fan and X. Xia, “A multi-objective optimization model for building envelope retrofit planning,” *Energy Procedia*, vol. 75, pp. 1299–1304, 2015.

## LIST OF ABBREVIATIONS

GA	Genetic algorithm
EPC	Energy performance certificate
LEED	Leadership in Energy and Environmental Design
USGBC	United States Green Building Council
SEER	Seasonal energy efficiency ratio
HSPF	Heating seasonal performance factor
HVAC	Heating, ventilation and air conditioning
NPV	Net present value
PV	Photovoltaics
NMIP	Nonlinear mixed-integer programming
VIP	Vacuum insulation panel
EPS	Expanded polystyrene
SPF	Sprayed polyurethane foam
US	United States
EU	European Union
ERDC	Engineer Research and Development Center
CO <sub>2</sub>	Carbon dioxide
°C	Degrees Celsius
MWh	Mega-Watt hour
Btu	British thermal unit
Wh	Watt hour
kW	kilo-Watt
W	Watt
h	hour
L	liter
\$	dollar
m	meter
s	second
kg	kilogram

# TABLE OF CONTENTS

<b>CHAPTER 1</b>	<b>INTRODUCTION</b>	<b>1</b>
1.1	BUILDING ENERGY CONSUMPTION	1
1.2	GREEN BUILDING POLICIES	2
1.3	LITERATURE REVIEW	4
1.3.1	Building energy efficiency overview	4
1.3.2	Green building and green retrofit	7
1.3.3	Methodologies	10
1.3.4	Research gap	11
1.4	RESEARCH MOTIVATION AND OBJECTIVES	13
1.5	CONTRIBUTION AND LAYOUT OF THESIS	14
<b>CHAPTER 2</b>	<b>BUILDING ENVELOPE RETROFIT CONSIDERING PV SYSTEM INSTALLATION AND MAINTENANCE</b>	<b>17</b>
2.1	INTRODUCTION	17
2.2	SYSTEM MODELING	20
2.2.1	Degradation model of PV system	20
2.2.2	Energy production of PV system	22
2.2.3	Energy consumption for space heating	22
2.2.4	Energy consumption for space cooling	24
2.2.5	Energy consumption for water heating	25
2.3	OPTIMIZATION	25
2.3.1	Decision variables	25
2.3.2	Objectives	26
2.3.3	Constraints	28
2.4	CASE STUDY	29



2.4.1	Case information . . . . .	29
2.4.2	Algorithm selection . . . . .	32
2.4.3	Results with GA . . . . .	33
2.4.4	Results with $w_1 = 0.7, w_2 = 0.2$ and $w_3 = 0.1$ . . . . .	33
2.4.5	Results with $w_1 = 0.1, w_2 = 0.2$ and $w_3 = 0.7$ . . . . .	36
2.4.6	Sensitivity analysis . . . . .	38
2.5	CONCLUSION . . . . .	40
<b>CHAPTER 3 BUILDING RETROFIT PLANNING FOR EPC COMPLIANCE . . .</b>		<b>42</b>
3.1	INTRODUCTION . . . . .	42
3.2	SYSTEM MODELING . . . . .	44
3.2.1	Energy consumed by cooling load . . . . .	44
3.2.2	Energy consumed by heating load . . . . .	47
3.2.3	Energy consumed by lights and appliances . . . . .	48
3.2.4	Energy production of PV system . . . . .	48
3.2.5	Total energy consumption of a building . . . . .	49
3.2.6	Energy intensity of a building . . . . .	49
3.3	OPTIMIZATION . . . . .	50
3.3.1	Decision variables . . . . .	51
3.3.2	Objectives . . . . .	52
3.3.3	Constraints . . . . .	53
3.4	CASE STUDY . . . . .	54
3.4.1	Case information . . . . .	54
3.4.2	Results with $w_1=0.7, w_2=0.3$ . . . . .	57
3.4.3	Results with $w_1=0, w_2=1$ . . . . .	60
3.4.4	Results with $w_1=1, w_2=0$ . . . . .	62
3.4.5	Results comparison with different weighting factors . . . . .	65
3.5	CONCLUSION . . . . .	67
<b>CHAPTER 4 BUILDING RETROFIT OPTIMIZATION MODELS USING NOTCH TEST DATA . . . . .</b>		<b>69</b>
4.1	INTRODUCTION . . . . .	69
4.2	PROBLEM DESCRIPTION . . . . .	72
4.3	OPTIMIZATION METHOD I . . . . .	74

4.3.1	Decision variables . . . . .	74
4.3.2	Objectives . . . . .	74
4.3.3	Objective function . . . . .	75
4.3.4	Constraints . . . . .	75
4.4	OPTIMIZATION METHOD II . . . . .	76
4.4.1	Decision variables . . . . .	77
4.4.2	Objectives . . . . .	77
4.4.3	Objective function . . . . .	78
4.4.4	Constraints . . . . .	78
4.5	CASE STUDY . . . . .	78
4.5.1	Case information . . . . .	78
4.5.2	Data collection . . . . .	80
4.5.3	Results analysis of optimization method I . . . . .	90
4.5.4	Results analysis of optimization method II . . . . .	95
4.5.5	Comparison of the two methods . . . . .	99
4.6	CONCLUSION . . . . .	100

**CHAPTER 5 OPTIMAL MAINTENANCE PLAN FOR BUILDING ENVELOPE INSULATION SYSTEM AFTER RETROFIT . . . . . 102**

5.1	INTRODUCTION . . . . .	102
5.2	SYSTEM MODELING . . . . .	103
5.2.1	Thermal performance decay model . . . . .	104
5.2.2	Energy consumption of the building . . . . .	104
5.3	OPTIMIZATION . . . . .	105
5.3.1	Decision variables . . . . .	106
5.3.2	Objectives . . . . .	106
5.3.3	Constraints . . . . .	107
5.4	CASE STUDY . . . . .	108
5.4.1	Case information . . . . .	108
5.4.2	Results analysis . . . . .	110
5.5	CONCLUSION . . . . .	113

**CHAPTER 6 CONCLUSION AND FUTURE WORK . . . . . 114**

6.1	CONCLUSION . . . . .	114
-----	----------------------	-----

6.2 FUTURE WORK . . . . . 116

## LIST OF TABLES

2.1	Parameters of windows . . . . .	30
2.2	Parameters of external wall insulation materials . . . . .	31
2.3	Parameters of roof insulation materials . . . . .	31
2.4	Parameters of solar panels . . . . .	32
2.5	Results with $w_1 = 0.7$ , $w_2 = 0.2$ and $w_3 = 0.1$ . . . . .	35
2.6	Results with $w_1 = 0.1$ , $w_2 = 0.2$ and $w_3 = 0.7$ . . . . .	37
3.1	Energy performance scale . . . . .	50
3.2	Information on window alternatives . . . . .	56
3.3	Information on chiller alternatives . . . . .	56
3.4	Information on heat pump alternatives . . . . .	56
3.5	Information on lighting technology alternatives . . . . .	57
3.6	The optimal solution with weighting factors $w_1 = 0.7$ , $w_2 = 0.3$ . . . . .	58
3.7	The optimal solution with weighting factors $w_1 = 0$ , $w_2 = 1$ . . . . .	61
3.8	The optimal solution with weighting factors $w_1 = 1$ , $w_2 = 0$ . . . . .	64
4.1	Window alternatives . . . . .	79
4.2	Wall insulation material alternatives . . . . .	79
4.3	Roof insulation material alternatives . . . . .	80
4.4	Chiller alternatives . . . . .	80
4.5	Heat pump alternatives . . . . .	80
4.6	Solar panel alternatives . . . . .	80
4.7	Lighting technology alternatives . . . . .	81
4.8	Notch test data of retrofitting a floor's envelope and the building's HVAC system (part 1)	82
4.8	Notch test data of retrofitting a floor's envelope and the building's HVAC system (part 2)	83
4.8	Notch test data of retrofitting a floor's envelope and the building's HVAC system (part 3)	84

4.8	Notch test data of retrofitting a floor's envelope and the building's HVAC system (part 4)	85
4.8	Notch test data of retrofitting a floor's envelope and the building's HVAC system (part 5)	86
4.9	Notch test data of retrofitting the lighting system of one floor (part 1)	87
4.9	Notch test data of retrofitting the lighting system of one floor (part 2)	88
4.10	Notch test data of retrofitting the roof considering the HVAC retrofit (part 1)	89
4.10	Notch test data of retrofitting the roof considering the HVAC retrofit (part 2)	90
4.11	Notch test data of installing one solar panel	90
4.12	Results of applying optimization method I with different budgets	91
4.13	Results of applying optimization method II with different budgets	96
5.1	Detailed information on sprayed polyurethane insulation materials	108
5.2	Detailed information on new windows	108
5.3	Performance of optimized solutions with different budgets	110

## LIST OF FIGURES

2.1	Structure of an apartment in the building under study . . . . .	30
2.2	Convergence of the GA algorithm . . . . .	34
2.3	Sensitivity analysis of the discount rate . . . . .	39
3.1	Floor plan of the office building under study . . . . .	55
3.2	Impact of tax incentive on the retrofit project with $w_1 = 0.7, w_2 = 0.3$ . . . . .	60
3.3	Impact of tax incentive on the retrofit project with $w_1 = 0, w_2 = 1$ . . . . .	63
3.4	Impact of tax incentive on the retrofit project with $w_1 = 1, w_2 = 0$ . . . . .	65
3.5	Optimal results with different weighting factors considering tax incentive . . . . .	66
3.6	Optimal results with different weighting factors, not considering tax incentive . . . . .	67
4.1	Structure of one floor of the office building under study . . . . .	79
4.2	Optimal results obtained by optimization method I with different weighting factors . . . . .	93
4.3	Impact of tax incentive on the optimal results obtained by optimization method I with $w_1 = 0.8, w_2 = 0.2, \beta = \$10000$ . . . . .	94
4.4	Optimal results obtained by optimization method II with different weighting factors . . . . .	98
4.5	Impact of tax incentive on the optimal results obtained by optimization method II with $w_1 = 0.8, w_2 = 0.2, \beta = \$10000$ . . . . .	99
5.1	Structure of the family house under study. . . . .	109
5.2	U-value changes of external walls and roof over the evaluation period. . . . .	112

## LIST OF SYMBOLS

$\beta$  total investment of the building envelope retrofit project

$x_i^{win}(t)$  retrofit state of the  $i$ -th alternative of the windows in year  $t$

$\alpha$  exterior envelope solar radiation absorption coefficient

$\alpha_1$  power load densities of people

$\alpha_2$  power load densities of lighting

$\alpha_3$  power load densities of appliances

$\bar{C}_f(M)$  absolute value of the cumulative cash flow at the end of the  $M$ -th month

$\beta_t$  budget allocated to year  $t$

$\delta(t)$  EPC rating coefficient

$\Delta E_{cool}(t)$  difference of the energy consumption before and after the retrofit for space cooling

$\Delta E_{heat}(t)$  difference of the energy consumption before and after the retrofit for space heating

$\Delta E_{water}(t)$  difference of the energy consumption before and after the retrofit for water heating

$\Delta W(t)$  humidity ratio difference between the inside air and outdoor air in year  $t$

$\delta_i$  effective solar energy transmittance of the  $i$ -th type window

$\eta_a$  domestic water heating system efficiency

$\eta_p$  efficiency of the  $p$ -th alternative of the solar panels

$\eta_s$  average solar energy to electrical power conversion efficiency

$\mathcal{L}$  lifespan of solar panels

$\lambda_j$  thermal conductivity of the  $j$ -th alternative of the external wall insulation materials

$\lambda_k$  thermal conductivity of the  $k$ -th alternative of the roof insulation materials

$\lambda_r$  thermal conductivities of the roof insulation material used for the retrofit

$\lambda_w$  thermal conductivities of the external wall insulation material used for the retrofit

$\mu$  heat gains utilization factor

$\Psi$  linear heat flux transmission

$\theta_m$  average outdoor temperature in the cooling season

$\varphi$  scale parameter

$\zeta_a$  allowance rate

$\zeta_t$  tax rate



$a$  a positive integer

$A^{pv}(p)$  area of one solar panel of the  $p$ -th option

$A_e$  effective glazing solar radiation collector area for the windows with different orientations

$A_i$  area of non-heated spaces

$A_p$  net floor area

$A_p^{pv}$  area of one solar panel of the  $p$ -th alternative

$A_{eff}$  available roof area for the PV system installation

$A_{flr}$  area of the floor

$A_g$  gross area of the building

$A_{rof}$  area of the roof

$A_{wal}$  area of the walls

$A_{win}$  area of the windows

$ACH$  air changes per hour

$B$  interior length of the contact between the floor or wall interior linear perimeter and soil or thermal bridge interior length

$BLC_{ext}$  building load coefficient

$C$  number of chiller alternatives

$C(t)$  retrofit cost in year  $t$

$C^{hva}(v)$  cost of retrofitting the HVAC system with its  $v$ -th option

$C^{lig}(u)$  cost of retrofitting one floor's lighting system with the  $u$ -th option

$C^{lig}(u_f)$  cost of retrofitting the lighting system of the  $f$ -th floor with its  $u_f$ -th option

$C^{mix}(r)$  cost of retrofitting one floor's envelope and HVAC systems with the  $r$ -th option

$C^{mix}(v, e_f)$  cost of retrofitting the building's HVAC system with its  $v$ -th option and the envelope system of the  $f$ -th floor with its  $e_f$ -th option

$C^{pv}(p)$  cost of one solar panel of the  $p$ -th option

$C^{rof}(k)$  cost of retrofitting the roof with its  $k$ -th option

$C_c^{chi}$  cost of the  $c$ -th alternative of the chillers

$C_f(M)$  discounted cash flow in the  $(M)$ -th month

$C_h^{pum}$  cost of the  $h$ -th alternative of the heat pumps

$C_i^{win}$  cost of the  $i$ -th alternative of the windows

$C_j^{wal}$  cost of the  $j$ -th alternative of the external wall insulation materials

$C_k^{rof}$  cost of the  $k$ -th alternative of the roof insulation materials

$C_l$  air latent heat factor

$C_m(t)$  maintenance cost in year  $t$

$C_p^{pv}$  unit cost of the  $p$ -th alternative of the solar panels

$C_r$  retrofit cost of the retrofit project

$C_s$  air sensible heat factor

$C_{dd}(t)$  cooling degree days in year  $t$

$C_{l_m}^{lig_m}$  unit cost of the  $l_m$ -th alternative of the lighting used to retrofit the  $m$ -th type of existing lighting technologies

$C_{m_p}^{pv}$  unit maintenance cost of the  $p$ -th type solar panel

$C_{r1}$  cost of the building retrofit project

$C_{r2}$  cost of the building retrofit project

$C_{rof}$  cost of roof insulation material

$C_{tot}$  total cost of the building retrofit project

$C_{wal}$  cost of wall insulation material

$C_{win}$  cost of new windows

$d$  discount rate

$D(t)$  number of solar panels that still work properly at the end of year  $t$

$d_j$  thickness of the  $j$ -th alternative of the external wall insulation materials

$d_k$  thickness of the  $k$ -th alternative of the roof insulation materials

$d_r$  thicknesses of the insulation materials added to the roof

$d_w$  thicknesses of the insulation materials added to the external walls

$d_{r,g}$  thicknesses of the roof insulation material applied during the  $g$ -th maintenance activity

$d_{w,g}$  thicknesses of the external wall insulation material applied during the  $g$ -th maintenance activity

$e$  retrofit option for the envelope system

$E_e$  heat gain through the envelope

$e_f$  the  $e_f$ -th option for the envelope system chosen for retrofitting the  $f$ -th floor

$E_i$  internal heat gains

$E_p(t)$  energy performance of a building in year  $t$

$E_r$  reference net annual energy consumption

$E_t$  heat transfer due to infiltration

$E_v$  heat loss through fresh air flow

$E_{base}$  baseline energy consumption

$E_{cool}(t)$  energy consumed by the cooling load in year  $t$

$E_d(t)$  energy consumed by the lighting and appliances in year  $t$

$E_{enu}$  heat loss through zones in contact with non-useful spaces

$E_{ext}$  heat loss through zones in contact with the outdoor environment

$E_{gu}$  useful heat gains

$E_{heat}(t)$  energy consumed by the heating load in year  $t$

$E_i(t)$  internal heat gain in year  $t$

$E_{lc}(t)$  infiltration and ventilation latent heat gain of the cooling load in year  $t$

$E_{lh}(t)$  infiltration and ventilation latent heat loss in year  $t$

$E_{post}$  total energy consumption after retrofit

$E_{pre}$  total energy consumption before retrofit

$E_{pt}$  heat loss through linear thermal bridges

$E_{pv}(t)$  energy production of the PV system in year  $t$

$E_{sc}(t)$  infiltration and ventilation sensible heat gain of the cooling load in year  $t$

$E_{sh}(t)$  infiltration and ventilation sensible heat loss in year  $t$

$E_{sl}(t)$  solar heat gain of the cooling load in year  $t$

$E_{tc}(t)$  transmission heat gain of the cooling load in year  $t$

$E_{th}(t)$  transmission heat loss in heating season in year  $t$

$E_{tot}(t)$  total energy consumption of the building in year  $t$

$E_{water}$  energy consumption for water heating

$ES(t)$  energy savings in year  $t$

$ES^{lig}(u)$  energy savings of retrofitting one floor's lighting system with the  $u$ -th option

$ES^{lig}(u_f)$  energy savings of the  $f$ -th floor after its lighting system has been retrofitted with the  $u_f$ -th option

$ES^{mix}(r)$  energy savings of retrofitting one floor's envelope and the building's HVAC system with the  $r$ -th option

$ES^{mix}(v, e_f)$  energy savings of the  $f$ -th floor after its envelope system retrofitted with the  $e_f$ -th option and the building's HVAC system retrofitted with the  $v$ -th option

$ES^{pv}(p)$  energy production of one solar panel of the  $p$ -th option

$ES^{rof}(k, v)$  energy savings of retrofitting the roof of the building with its  $k$ -th option when the  $v$ -th HVAC option is retrofitted

$ES_1(t)$  energy savings of the building after retrofitting in year  $t$

$ES_2(t)$  energy savings of the building retrofit project in year  $t$

$ES_{tot}$  total energy savings after retrofit

$F$  number of floors

$g$  a positive integer

$G_{south}$  average solar energy that reaches a south-oriented vertical surface

$H$  number of heat pump alternatives

$H_{dd}(t)$  heating degree days in year  $t$

$HSPF(t)$  heating seasonal performance factor in year  $t$

$HSPF_h$  performance coefficient of the  $h$ -th alternative of the heat pumps

$I$  number of window alternatives

$I_r$  average solar radiation intensity

$I_{pv}(t)$  solar irradiation on the PV system in year  $t$

$I_{win}(t)$  solar irradiance on the windows in year  $t$

$J$  number of wall insulation material alternatives

$K$  number of roof insulation material alternatives

$k$  retrofit option for the roof system

$L_m$  number of lighting alternatives for the  $m$ -th type of existing lighting

$M$  month after the investment at which cumulative discounted cash flow occurs

$m$  number of existing lighting types

$M(t)$  number of solar panels installed during maintenance in year  $t$

$M_h$  heating season duration

$M_a$  average daily water consumption

$n_d$  number of days when domestic water heating occurs

$N_f^{env}$  number of floors to retrofit envelope systems

$N_f^{lig}$  number of floors to retrofit lighting systems

$N_p(t)$  number of solar panels that work properly at the beginning of year  $t$

$N_p^0$  number of solar panels installed at the beginning of the retrofit project

$N_{l_m}$  maximum number of  $m$ -th type of existing lamps available for retrofit

$N_{lig_m}(t)$  retrofit number of the  $m$ -th type of existing lighting technology in year  $t$

$N_{pv}(t)$  number of selected solar panels to be installed in year  $t$

$NPV$  net present value

$P$  number of solar panel alternatives

$p$  retrofit option for the PV system

$p(t)$  electricity price in year  $t$



$P_a$  total power of appliances per year

$P_d$  height from floor to ceiling

$P_l(t)$  total power of the lighting in year  $t$

$q_i$  internal gains

$Q_s$  air flow rate

$r$  retrofit option for the combined system including the envelope and HVAC

$R(t)$  tax incentive in year  $t$

$R_d(t)$  survival rate of solar panels at time  $t$

$R_p(t)$   $R$ -value of sprayed polyurethane at time  $t$

$SEER(t)$  seasonal energy efficiency ratio in year  $t$

$SEER_c$  performance coefficient of the  $c$ -th alternative of the chillers

$SHGC(t)$  solar heat gain coefficient in year  $t$

$T$  project period

$T_c(t)$  cooling time in year  $t$

$T_h(t)$  heating time in year  $t$

$T_m$  maintenance interval

$T_p$  payback period

$T_s(t)$  solar irradiation time in year  $t$

$T_d(t)$  occupancy time of the lighting and appliances in year  $t$

$T_{oc}(t)$  occupancy time in the cooling season in year  $t$

$T_{p1}$  payback period of the building retrofit project

$T_{p2}$  payback period of the building retrofit project

$u$  retrofit option for the lighting system

$u_f$  the  $u_f$ -th option for the lighting system chosen for retrofitting the  $f$ -th floor

$U_i$  thermal transmittance of the  $i$ -th alternative of windows

$U_n$  thermal transmission coefficient in non-useful space

$U_r$  thermal transmittance of the roof before retrofit

$U_w$  thermal transmittance of the walls before retrofit

$U_{flr}(t)$  thermal transmittance of the floor in year  $t$

$U_{rof}(t)$  thermal transmittance of the roof in year  $t$

$U_{wal}(t)$  thermal transmittance of the walls in year  $t$

$U_{win}(t)$  thermal transmittance of the windows in year  $t$

$v$  retrofit option for the HVAC system

$w_1$  positive weight

$w_2$  positive weight

$w_3$  positive weight

$x_c^{chi}(t)$  retrofit state of the  $c$ -th alternative of the chillers in year  $t$

$x_p^{pv}(t)$  retrofit state of the  $p$ -th alternative of the solar panels in year  $t$

$x_{l_m}^{ligm}(t)$  retrofit state of the  $l_m$ -th alternative of the lighting for retrofitting the  $m$ -th type of existing lighting in year  $t$

$Z_i$  orientation coefficient for different facades

$x_h^{pum}(t)$  retrofit state of the  $h$ -th alternative of the heat pumps in year  $t$

$x_j^{wal}(t)$  retrofit state of the  $j$ -th alternative of the wall insulation materials in year  $t$

$x_k^{rof}(t)$  retrofit state of the  $k$ -th alternative of the roof insulation materials in year  $t$

# CHAPTER 1 INTRODUCTION

## 1.1 BUILDING ENERGY CONSUMPTION

The impact of buildings on global warming and climate change as well the resource consumption and waste generation is well recognized, namely<sup>1</sup>,

- over a third of all CO<sub>2</sub> emissions results from the construction and operations of buildings;
- over a third of all energy and material resources are used to construct and operate buildings; and
- over a third of total waste is due to construction and demolition activities.

Looking at energy usage alone, the building sector is responsible for a large portion of global energy consumption, as evidenced by the staggering 32% energy usage out of the total energy consumed in the world. Statistics show that this number even reaches 40% in the European Union (EU) [1, 2]. This high level of consumption is mostly associated with existing buildings, given the low rate of new constructions across the globe (about 1%-3% per year [3, 4]).

Efficient utilization of energy in existing buildings is thus an urgent task to mitigate the environmental footprint of the building sector. To this end, various initiatives and methodologies can be applied. Whereas the technologies are globally developed in the modernized world, different policy supports and initiatives to promote a green building sector are usually in place in different regions and countries.

---

<sup>1</sup>South African Department of Public Works. Public Works Green Building Policy. 2013

In view of the easy access to the most advanced technologies across the world for most countries, policy support and decision making support play a more important role in today's energy efficiency improvement activities.

## 1.2 GREEN BUILDING POLICIES

On a global scale, the main driver of energy consumption reduction in buildings is the common challenge, global warming, faced by the human race. This has resulted in various agreements and protocols being entered into by participating countries to actively reduce their greenhouse gas emissions through various sectors, such as the industrial, transportation and building sectors, etc. These types of agreements and protocols, such as the Kyoto Protocol <sup>2</sup> and the Paris Agreement <sup>3</sup>, help to shape global energy consumption patterns by making countries aware of the negative effects of greenhouse gas emissions associated with the consumption of fossil fuels. This awareness then leads to national regulations and policies through which clear targets of emission reduction are set for different sectors in order to facilitate the transition to a cleaner society.

The building sector has a direct impact on global climate change because it is responsible for about 40% of total energy consumption in the EU and United States (US), where it out-consumes both the transportation and industrial sectors. Energy intensity reduction of buildings in urban areas is essential to reduce the environmental impact of the building sector, because buildings account for about 70% of global energy consumption and more than 70% of greenhouse gas emissions [5]. The global population is predicted to increase to 8.5 billion by 2030, calling for the construction of more than 80 billion buildings – an area roughly equal to 60% of the total global building stock. It is of crucial importance to make use of green building technologies for both existing buildings and new constructions. To achieve the 2 degrees Celsius temperature increase by 2030 target set by the COP21 Paris climate conference, the World Green Building Council (WGBC) pointed out that the globe must reduce 84 gigatons of CO<sub>2</sub> by 2050 in the building sector alone [6].

Currently, driven by the EU's continuous development of policies and frameworks for building environmental performance indices and legally binding legislation, European countries are leading

---

<sup>2</sup>Paris Agreement, entered into force on 4 November 2016.

<sup>3</sup>Kyoto Protocol, entered into force on 16 February, 2005.

the global green building sector<sup>4</sup>. Other countries, such as the US, Australia, China, etc., are also developing their own legislation promoting the transition to a green building sector. For example, the Leadership in Energy and Environmental Design (LEED) certification program developed by the US Green Building Council, the Green Star rating system developed in Australia, and the evaluation standard for green building developed in China all aim to bring down the energy intensity of the building sector. Some countries, such as the EU countries and the US, even have more progressive initiatives that require new buildings to emit zero carbon by 2020 or 2030.

While, as mentioned before, enabling technologies for the transition to a green building sector are accessible to most nations, different policies are in place in different regions and countries to facilitate the market uptake of green technologies, such as on-site use of renewable energy resources like biomass and solar energy, optimal operation of in-house facilities and appliances, replacement of old technologies with more efficient counterparts, proper maintenance of building components and so on.

Individual countries usually have their own motivations for cleaner development not only because of their voluntary participation in global agreements, but also because of local needs. Pollution and energy shortage are, usually, among the most important local drives that force economies to be more energy efficient and more environmentally friendly in their economic development. For a specific country, both international and national policies and circumstances affect the dedication to energy consumption reduction.

South Africa, for an example, volunteered in the Kyoto Protocol to cut its carbon emissions and subsequently developed its national regulations, including the Integrated Resource Plan and Integrated Energy Plan, to facilitate this. Clear targets were set in those regulations as a result of participation in the international policies. Internally, the country had been facing severe challenges of electric power supply from its sole utility company, Eskom, to meet the growing demand resulting from economic and population growth<sup>5</sup>. Reducing energy consumption throughout the country while growing its gross domestic product was therefore a priority and promoted by many national policies and initiatives, including the national mass roll-outs of energy-efficient light bulbs, solar water geysers, etc., funded

---

<sup>4</sup>Newsroom. European Countries Lead in Global Green Building. <http://www.bakermckenzie.com/en/newsroom/2016/03/european-countries-lead-in-global-green-building/>. Accessed: 2017-08-08.

<sup>5</sup>Understanding the current energy crisis in South Africa. <http://www.theoilrum.com/node/3576>.

by the integrated demand management division of Eskom and many building retrofit projects funded by the South African Department of Energy through municipalities.

Reducing the energy intensity of buildings is beneficial for South Africa, where this study is conducted on two aspects. Firstly, constrained by its available power supply capacity, the country is trying to find every possible solution to balance power supply and demand. Reducing the energy consumption of the building sector is consequently a valid way of reducing power demand to mitigate the energy shortage problem. Secondly, as a member country of the WGBC, South Africa recognizes and acknowledges the importance of reducing the environmental footprint of the building sector. As a result, a particular focus on energy efficiency improvement for existing buildings was brought to the table by a localized green building policy compiled by the South African Department of Public Works. This newly updated green building policy requires all public buildings to be rated in terms of their energy efficiency and they must obtain a minimum required rating to satisfy a national standard for an energy performance certificate of buildings, developed specifically to support the green building policy [7].

In summary, there are both external (international) and internal (national) policies promoting the energy efficiency of the building sector in South Africa. This study is therefore undertaken to conduct research to support these policies by specifically reducing the energy intensity of existing buildings to make them greener.

## **1.3 LITERATURE REVIEW**

### **1.3.1 Building energy efficiency overview**

A building is a complex system that houses many different categories of components. From the energy efficiency perspective, the complexity of a building energy system can be described as follows. Firstly, a variety of energy carriers are involved in a building energy supply. For instance, the grid electricity, gas, energy from renewable resources like solar energy, wind energy, biomass, and so on. Secondly, a building consists of many subsystems and components required to provide various functionalities, such as services to the occupants. These include power supply, providing illumination, heating and cooling, humidity control, ventilation, cool and hot water supply, thermal insulation, shading, communication, office works, etc. Thirdly, there are significant interactions among the building components. For

example, the performance of all electrical appliances depends directly on the performance of power supply components. If the power quality fails to meet the appliance's requirement, the appliance's performance can deteriorate noticeably [8]. Another example is the interaction between the heating ventilation and air conditioner (HVAC) systems and the thermal insulation of the building, which influences the heat transfer between the building's internal and external spaces [9]. Lastly, the diverse energy sources, variety of functionalities and ubiquitous interactions among them result in the unique energy behavior of a building that manifests extreme complexity and flexibility.

On the other hand, such complexities and flexibilities suggest a variety of energy efficiency improvement opportunities in buildings. Most of the subsystems of a building reveal certain energy efficiency opportunities. For example, the development of technologies (e.g., the introduction of renewable energy sources [10] and microgrids [11]), the development of computer and communication technologies [12] and improvement in material science [13] all contribute to the energy efficiency improvement of a building. According to Wang and Xia [14], the vast energy efficiency opportunities can be categorized into four layers: the power quality layer, smart appliance layer, energy flow layer and planning layer. The explanations to these four layers are given in the following.

The power quality layer focuses on maintaining the power quality for a building energy system or microgrid. The power quality is evaluated by the following criteria: 1) the voltage regulation within a predefined range; 2) steady alternating current (AC) frequency and 3) smooth voltage waveform [15]. As aforementioned, the power quality can influence the performances of electrical appliances. It is therefore an extremely important topic that was thoroughly studied for conventional power systems. As a result of the introduction of renewable energy sources in buildings, the power quality issue reveals further influences on the building energy system. On the one hand, for the grid-tied systems, the grid-integration requires the power generated by renewable energy resources to meet the grid requirement. On the other hand, for the appliances in microgrid, the renewable energy resources are required to provide stable and high quality power supply, otherwise the appliances can be damaged. A variety of studies have been conducted for maintaining power quality in microgrids with renewable energy sources such as wind energy [16, 17, 18, 19, 20] and photovoltaic (PV) systems [21, 22, 23, 24]. The power quality control is realized by the inverter control [25, 26, 27] and/or direct current (DC) converter for energy storage systems [28, 29].

The smart appliance layer looks into enabling the context-awareness to the appliances in addition to the



built-in control logics. Such a context awareness results in further energy efficiency opportunities by means of taking into account the interactions between the appliances and the environment or occupant behaviors. For example, the lights can be turned on or off in response to the presence of occupants. Zhang and Xia [30] proposed a control strategy to optimize the lumen outputs of a lighting array in response to the monitored occupancy behavior. The energy performances of HVAC systems can also be improved by introducing the context awareness technologies. Mei and Xia [31] proposed a control framework that automatically determines the optimal working points of a HVAC system under specific indoor and external environmental conditions. Appliances can be further scheduled simultaneously to achieve an energy efficiency target. A series of studies on this topic were reported in [32, 33, 34], where household appliances are scheduled to maximize the cost effectiveness and energy savings. A recent paper on an integrated power dispatch and home appliance scheduling for a household PV-battery hybrid power system was reported in [35].

The energy flow layer aims at balancing energy inputs and outputs in an optimal manner in a building energy system. The grid supply is the major energy source in most buildings. However, the power demand of buildings are much higher during peak hours than that during off-peak hours [36], which leads to noticeably different loads for the grid over different time periods. In addition, the grid supply in rural areas can be limited in some cases [37]. Therefore, a mixture of different supplies, especially those including renewable energy resources, are introduced to supply power to buildings. This helps to mitigate grid strain by smoothing the demand profile and to provide a more reliable power supply to the building [38]. Moreover, the cost effectiveness and energy efficiency can be achieved by balancing the energy flows from multiple energy resources. For example, Tazvinga et al. [39, 40, 41] proposed an optimal energy flow scheduling approach for an off-grid PV-diesel-battery hybrid system. The usage of renewable energy resources is maximized such that the advantages of renewable energy sources are emphasized and the use of diesel and battery guarantees a continuous power supply.

The planning layer deals with the investment decisions to make the best use of limited resources, such as capital investment and manpower, to maximize the energy efficiency and cost effectiveness of an energy efficiency improvement project. For example, a large number of retrofit options can be involved in a building energy retrofit project. The performances of the retrofit options are evaluated at a large time scale up to 10 years. Thereafter, the optimal combination is selected from the candidate options to maximize the energy savings and cost-effectiveness. Asadi et al. [42] and Diaki et al. [43] proposed such optimization models for building energy retrofit, where a balance between the energy savings

and retrofit costs is struck. A planning layer issue is rather a management-level issue from the project viewpoint than the optimization and control of an individual appliance or corresponding subsystem. Achieving the optimal overall performances such as total energy savings are focused, while achieving the optimal energy performance of an individual appliance or subsystem is less concerned.

### 1.3.2 Green building and green retrofit

The preceding four layers are quite useful in identifying and organizing building energy efficiency opportunities, after which actual strategies to achieve energy efficiency improvement must be developed. Achieving building energy efficiency is within the scope of green building studies. The green building is a broad field that involves diverse research topics. According to Zuo and Zhao [44], there are mainly three categories of research topics from green buildings, namely, the definition and scope of green buildings, the quantification of the benefits of green buildings against conventional buildings and the technologies to achieve green buildings.

Over the last two decades, a number of green building assessment tools have been developed among many countries. For example, the Leadership in Energy and Environmental Design (LEED, United States), the BRE Environmental Assessment Method (BREEAM, United Kingdom), the Hong Kong Building Environmental Assessment Method (HK BEAM), the Green Star rating system developed by the Green Building Council of Australia (Green Star Australia, GBCA), the Green Star South Africa rating system (Green Star SA, South Africa), among others were reported in the literature. The majority of these assessment tools make use of a credit based evaluation that covers various aspects of the a building's sustainability, taking into account its energy efficiency, environmental impacts and human aspects. These assessment tools provide a thorough guideline to the design and operation of green buildings and promote the development of green building projects. For example, the LEED v2.2 has accredited over 5000 projects globally since its first launch in 2005 [45].

The green building retrofit planning (green retrofit) is the major method to address the growing energy demands and transform existing buildings into green ones. The green retrofit is a holistic planning problem that can involve all of the aforementioned energy efficiency opportunities. Such opportunities are realized by applying energy conservation measures (ECMs), which is defined as "used to mean measures to improve efficiency or conserve energy or water, or manage demand" [46], determined by

the retrofit planning process. The green retrofit, however, is a complicated problem because of the complexity of the building energy systems. As an example, there are interactions among the involved ECMs, either from the energy performance perspective or economic perspective. From the energy perspective, the interacting energy effects should be taken into account in the retrofit planning, which introduces coupling between different retrofit options. From the economic viewpoint, the candidate ECMs participate in the budget competition of retrofit planning. Ma et al. [3] interprets the retrofitting planning as "to determine, implement and apply the most cost effective retrofit technologies to achieve enhanced energy performance while maintaining satisfactory service levels and acceptable indoor thermal comfort, under a given set of operating constraints".

Existing studies on the green retrofit from the literature can be categorized into two general types, namely studies on determining the optimal retrofit plan for the indoor systems, including the lighting system, HVAC system, water heating system and plug loads; and studies that focusing on the envelope/enclosure of a building (including rooftop systems). With respect to indoor systems, many research papers has been published in recent years to select the best retrofit options such that certain objectives are achieved. Most of these work formulated the retrofit planning problem into multi-objective optimization problems considering energy savings, environmental impacts, economic benefits, etc., as the objectives (see, for example, [47, 48, 49, 50]).

In particular, Wang, Wu, Zhu and Xia [51] and Wang and Xia [52] introduced control system technology to tackle the retrofit planning problem for indoor appliances to reduce energy consumption. Optimization models for building indoor appliances retrofit considering a green building rating with reference to international protocols, such as LEED and Green Star, were also presented [53, 54, 55, 56]. In addition to energy-saving retrofits, studies also pointed out the importance of looking into the energy-water nexus in buildings [57, 58, 59]. Consequently, optimization models for energy and water savings in buildings were presented [60, 61, 62]. Motivated by the fact that the retrofitted items could fail after some time of operation, the maintenance schedule and intensity optimization of the retrofitted items were investigated and optimized following control system approaches in [52, 63].

On the one hand, these studies have already investigated the retrofit with a broad range of electrical appliances in buildings, including lighting, HVAC, water heating, and plug load systems either separately or together. On the other hand, the opportunities from retrofitting the building envelope are ignored. When it comes to the retrofit of envelope components, limited publications were found

in the literature. The main focus of researchers in this field was on the better design of the envelope, better insulating material development, and application of these designs and materials. For example, experimental and simulation based approaches were adopted to investigate the effect that materials with different thermal properties can have on the overall building's energy usage [64, 65, 66]. Some researchers [67, 68] conducted research on evaluating the impact of wall materials used in net-zero buildings. And some researchers [69, 70, 71, 72, 73] studied the modeling and constructional design of building envelopes in an effort to identify the best envelope design in order to improve thermal insulation of buildings by comparing different structures taking advantage of energy modeling techniques.

Research on the evaluation of different energy-saving materials and structures for use in building envelopes was also found in the literature [74, 75, 76, 77]. Lastly, some studies on the composition and structure of walls [78, 79, 80] and the owners' perception of the adoption of building envelope energy-efficient measures were studied [81].

While all of these studies add value to the energy efficiency improvement of building envelopes, the market uptake of the technologies developed is limited. Mainly because of missing information to the market and hesitation of decision makers regarding the new technologies. The unclear performance in terms of both energy savings and the financial implications of the new technologies restricts the application of these technologies. In other words, the newly developed technologies can improve the energy efficiency of buildings, but a decision support tool is missing for decision makers to bridge the gap between technology development and information available to building retrofit planners and managers. It is crucial to develop such a decision support tool that could be used by decision makers to evaluate the impact that the new technologies may have on a building and further help the decision makers to optimize the use of available technologies to obtain the maximum possible benefits in terms of energy savings and financial benefits.

Maintenance of envelope components is a subject neglected by the literature, mainly because of the relatively long life cycle of the envelope. However, maintenance must be taken into account for investment projects that require a performance guarantee and an accurate estimation of energy and cost savings over a long period. For this purpose, the author of this thesis developed optimization models for the maintenance planning of the retrofitted envelope components and installed rooftop PV systems in [82, 83].

Again, it was found that the studies on the envelope of buildings did not consider the impact of indoor appliances in a building. This is acceptable for building envelope component design but not ideal for green building retrofit plans where both the envelope and the indoor systems contribute to energy consumption and should be equally considered in the planning stage.

### 1.3.3 Methodologies

The green retrofit planning is essentially an optimization problem. Multiple optimization objectives are often involved in the green retrofit planning. A full building retrofit can take into account the energy performances, economic performance, human comfort, utilities of the appliances, environmental impact, etc. [84] The involved objectives are often conflicting. For example, reducing energy consumption will result in high retrofit costs. As a result, green retrofit planning usually requires the use of multi-criteria methodologies [85, 86, 87]. The focus of this study is on the building energy retrofit considering mainly the energy and economic performances of the retrofit project. The energy performances is evaluated by energy savings, i.e., the reduced energy consumption against the baseline energy consumption. The measurement and verification (M&V) methodology for energy savings is adopted to quantify the resulting energy savings [46]. Earlier studies used energy consumption as the performance indicator for retrofit option evaluation [42, 43]. Energy savings subject to the M&V methodology were adopted by Wang and Xia [4, 52] for the same purpose. The advantage of using energy savings instead of consumption as the performance indicator is that the contributions of the retrofit are emphasized. For the economic performance evaluation, a series of performance index from the finance and economy areas such as net present value (NPV), internal rate of return (IRR), overall rate of return (ORR), benefit-cost ratio (BCR), discounted payback period (DPP) and simple payback period (SPP) [88, 89] can be employed.

In order to solve the multi-objective optimization problems that are raised from the green retrofit, multi-objective optimization technologies must be introduced. One solution is to translate the multi-objective optimization problem into single objective equivalent problem by using a weighted sum of the objectives. This method was widely used to tackle the multi-objective optimization problems in the literature. For example, Malatji et al. [90] employed such a weighted sum approach. Two conflicting objectives, namely the energy savings and DPP were combined to a single objective. A non-stationary penalty function was adopted to indicate the constraints involved. The genetic algorithm (GA) was

employed as the numerical solver. In this way, Malatji et al. was able to figure out the optimal implementation plan for a large scale building energy retrofit project. Another solution is to investigate the trade-offs between the contradictory objectives. Wu et al. [91] employed such a multi-objective approach to obtain a series of non-dominated solutions. The term ‘non-dominated’ describes such a fact that one solution cannot be improved without degrading some of the other objective values [92]. The multi-objective approach offers a thorough understanding of the contradictory objectives to the decision maker, such that one can figure out a best solution considering the trade-offs of different objectives.

In addition to the optimization methodologies, control system approaches can be introduced in a class of green retrofit problems. Wang and Xia [52] investigated a maintenance planning problem in the building energy retrofit context. When taking into account the failures of the retrofits, i.e., the retrofitted equipment, the overall performances of a retrofit project manifest a certain level of dynamics, namely management level dynamics. The failures result in the deterioration of energy efficiency and other utilities, while the maintenance can reverse such a deterioration. A control system framework is identified to describe such dynamic relationships [14]. Accordingly, the preceding maintenance planning problems were interpreted into optimal control problems. Optimal control approaches were thereby introduced to tackle the aforementioned problems, providing a new perspective to the retrofit planning.

#### **1.3.4 Research gap**

Firstly, as mentioned in the preceding subsections, no study on the systematic retrofit plan for the whole building, including the envelope and the indoor systems, has been reported in the literature so far. Most of the existing studies focus on retrofit planning for indoor systems in a building, ignoring the envelope, which contributes up to 40% of the energy consumption of a building. This is mainly because the high initial investment required and the long payback period associated with the envelope retrofit [82, 93, 94, 95]. For instance, the research [94] pointed out that the payback period of retrofitting the indoor systems in a building is generally short while that of retrofitting the envelope system is around ten years. This perception of envelope retrofit has limited investigation in this category as well as practical implementation of envelope system retrofit. Studies on the envelope retrofit are very scarce and the limited number of publications that could be found on this topic did not look into the indoor

energy consuming systems in a building, because these studies on envelope systems primarily focused on improving either specific structures of the envelope or insulation materials used in envelope to decrease energy dissipated through the enclosure of a building. Envelope retrofit was not particularly studied because of the long payback period involved. Only a few studies can be found in the literature that tries to investigate the benefits of envelope retrofit. However, those studies looked at the envelope system together with renewable systems but the indoor energy consuming facilities are not considered. With the decreasing cost of appliances and envelope materials nowadays, it is possible to identify building retrofit plans that consider both the indoor and envelope systems in a systematic approach, which will ensure the maximum possible energy savings can be achieved and, at the same time, reach a reasonable financial return of the project. This is possible because the long term investment of the envelope system can be mitigated by the short payback of indoor system retrofit and the envelope renovation brings more energy savings. In addition, the technical difficulty associated with solving the retrofit problem, which is usually a mixed integer programming problem, also restricts researchers to formulate and solve a retrofit planning problem efficiently, considering both indoor appliances and the envelope. In particular, the problem can be formulated as a linear mixed integer problem when only indoor appliances are considered. When the envelope comes into play, however, the problem becomes highly nonlinear and of high-dimension, which is difficult to solve mathematically. Therefore, the first research gap identified is the lack of a systematic retrofit optimization model for buildings considering both the indoor systems and the envelope.

Secondly, although studies on green building rating and building energy performance contracting projects were recently reported [54, 96] in the literature, none of them can be used to support decision makers who are concerned with building retrofit investment under South African's localized green building policy compliance with regard to the recently developed energy performance certificate (EPC) rating system (see section 1.2). This is mainly because of the recent nature of the EPC standard introduced. Studies on green building rating with respect to international standards, such as LEED and green star, take into account many factors such as waste management, indoor air quality, etc., but not specifically focus around the energy intensity of a building. Essentially, the EPC rating looks at the energy intensity of a whole building, which naturally calls for a systematic whole-building retrofit approach. Coupled with the technical difficulty of solving the systematic retrofit problem mentioned earlier, there is a need to investigate the whole-building retrofit problem considering the EPC rating and identify or develop methods to solve the resulting optimization problem efficiently.

This study aims at filling the aforementioned research gap. The envelope retrofit, whole building retrofit and retrofit planning for EPC compliance have been investigated accordingly. The layout of the main contributions are introduced as follows.

#### **1.4 RESEARCH MOTIVATION AND OBJECTIVES**

Noting that existing buildings consume a considerably large amount of energy internationally and that there are global and national pushes towards more energy-efficient and greener building sectors, this study investigates the problem related to green retrofit of existing buildings to make them more energy-efficient and more environmentally friendly and also to make them comply with the South African green building policy, subject to the EPC rating of buildings.

Motivated by the fact that enabling technologies for green building retrofit are accessible in most parts of the world, including South Africa, this work focuses on developing a useful decision support tool to help decision makers to determine optimal retrofit plans and investments to maximise the resulting benefits. The second objective of this work is, through provision of such a decision support tool, to enable investment decision makers to make more informed decisions on green building retrofit projects to facilitate market uptake of advanced technologies in improving the energy efficiency of existing buildings and ultimately promote a green building sector.

In addition, this study will also be useful for current public building owners and all building owners in the near future to identify the most effective retrofit options for their buildings in order to comply with the green building policy when the target building groups of the green building policy are extended to include all types of buildings. This is particularly true given the recent nature of the green building policy and the limited experience of the country in this type of project. In terms of technical and methodology developments, this thesis aims to investigate the green building retrofit problem in a systematic manner and propose mathematical methods that can be used to determine the optimal retrofit plans for buildings, taking into account all energy consuming facilities and devices. Moreover, this thesis will also target developing methods that can be used to solve the whole-building retrofit problem efficiently and effectively, owing to the difficulty of solving the high-dimension nonlinear mixed integer programming problem.



## 1.5 CONTRIBUTION AND LAYOUT OF THESIS

The main contributions of this thesis are summarized in three journal articles and several conference papers. Two more journal articles on this topic are currently under construction. A brief summary of these contributions are listed below:

- A whole-building retrofit planning problem is formulated and solved, which can be used as a decision support tool for decision makers and building owners for green building retrofit projects.
- The retrofit plan considers all possible items that can be retrofitted to reduce the energy intensity of a building, including in-house facilities and appliances, the envelope of a building and rooftop systems.
- The retrofit planning for buildings that need to comply with the green building policy in terms of the energy performance certificate is formulated and solved.
- Methods to solve whole-building retrofit problems effectively and efficiently are developed and analyzed. These methods are particularly developed to reduce the complexity of solving the nonlinear mixed integer optimization problems. The methods are also useful in terms of reducing cost associated with energy audit of the building to be retrofitted and can be used as a guideline for a quick estimation of the energy intensity reduction potential of a building.
- The effect of maintenance of retrofitted items on the overall performance of the green building retrofit is investigated.

Aligning to the research objectives, this PhD research is divided into four subproblems. Firstly, the building envelope retrofit planning is investigated. Secondly, based on the results of the first part and studies found in the literature, a systematic whole-building retrofit problem is investigated. Thirdly, methods to reduce the complexity and consequently help to solve the whole-building retrofit problem efficiently is studied in view of the difficulty to solve the problem formulated in the third part. After that, the problem of performance degradation of retrofitted items and corresponding maintenance planning are studied.

The following chapters of this thesis are organized according to the subproblems and published papers and are organized as follows.

Chapter 2 presents an optimization model for building envelope retrofit planning, which takes the facility performance degradation and economic feasibility of the retrofitting into consideration to support decision makers. The important indicators of an investment including the energy savings, net present value (NPV) and the payback period are directly built into the optimization model and optimized, not only to run after a profitable building retrofit plan, but also to enable decision makers to make an informed decision. In addition, the optimal selection and sizing of a rooftop PV power supply system are formulated into the proposed retrofit planning model to reduce the demand of electricity generated from fossil fuels in the light of the adequate solar resource in South Africa. The optimization model also takes into account the maintenance costs of the retrofitted items over the project period, which are usually ignored in the existing literature, to obtain an accurate estimation of the savings potential and consequently an accurate payback period estimation for the decision maker.

Chapter 3 presents a systematic approach to the whole-building retrofit considering, both the envelope and the indoor facilities for the purpose of green building compliance with reference to the EPC rating system. The proposed model determines the optimal retrofit plan for a given building to ensure that the desired EPC rating is obtained in a cost-effective manner, i.e., the resulting energy savings are maximized, and the payback period of the investment is minimized using an optimization approach. Moreover, the proposed model treats the retrofit plan as a multi-year project with improving efficiency targets in consecutive years. This is considered because retrofitting a building to obtain the best rating usually requires a significant amount of investment with a long payback period. In view of the current economic uncertainties in South Africa, projects with long payback periods are not attractive to investors. As such, breaking up the retrofit into smaller projects over multiple financial years will help to mitigate the concerns of the investors. This essentially will make sure that at least the so-called ‘low-hanging fruits’ projects, which generate noticeable savings with a relatively small investment, for energy efficiency improvement will be implemented in the starting years of the retrofit project. Compared to once-off long-term investments, the solution provided by this study will help to break down the project into smaller projects with shorter payback periods that are more attractive for decision makers. In addition, available incentives for energy saving projects in South Africa are considered in this model.

In a building retrofit project, there are a number of systems and items to be retrofitted, which results in a large number of decision variables that are either integers or binaries in the optimization problem presented in Chapter 3. The intrinsic multi-objective and non-linearity characteristic of the optimization problem makes it very difficult to solve. Besides, the complexity of the optimization problem increases dramatically when the buildings to be retrofitted have many floors. In addition to this challenge, the optimization problem requires a detailed bottom-up audit of target buildings, which is expensive. Thus, Chapter 4 puts forward two methods to reduce the detail level of the required audit and the complexity of solving the optimization problem formulated in Chapter 3.

Chapter 5 deals with the optimal maintenance planning for the retrofitted items to ensure sustainable performance. In particular, it presents an optimal maintenance strategy for the envelope components that are retrofitted. Maintenance of indoor facilities and the rooftop PV systems were not considered in this chapter because the indoor appliance maintenance problem has been studied and solved by some colleagues working in the Center of New Energy Systems at the University of Pretoria [52, 63] and the rooftop PV system maintenance was included in the model presented in Chapter 2.

Finally, Chapter 6 concludes this thesis and puts forwards some suggestions for future work.

# **CHAPTER 2 BUILDING ENVELOPE RETROFIT CONSIDERING PV SYSTEM INSTALLATION AND MAINTENANCE**

## **2.1 INTRODUCTION**

The energy consumed by the building sector constitutes a large proportion of the total energy consumption of the world. In particular, the envelope system of a general building takes large responsibility for its total energy usage [97]. Therefore, improving the energy performance of building envelope systems by retrofitting them with energy-efficient facilities is an economical and effective method to make existing buildings more energy-efficient [4, 91, 98].

In this chapter, an optimization method for building envelope retrofit planning is proposed. For the building envelope retrofit project, the main envelope components are considered to be retrofitted to reduce heat transfer between the indoor and outdoor environments. For instance, it is considered to retrofit the windows of the building with better alternatives and to install insulation materials on the walls and roof. Because of the adequate solar resource in South Africa, a rooftop PV power supply system is also considered to be installed, the purpose of which is to reduce the building's energy demand from the grid and ensure better life quality of the occupants by protecting the building from unpredictable power failure [99] and reducing the emission of CO<sub>2</sub> [100]. Although PV system is often regarded as reliable, the energy performance of the system degrades over time [101], which influences the power generation of the PV system [102, 103] and also the building envelope retrofit plan. Hence, the performance degradation of the PV power supply system and corresponding maintenance

of the system are built into the optimization process to ensure an accurate estimation of the potential energy savings and the sustainability of the energy savings of the building envelope retrofit project. The maintenance actions for the PV system are scheduled at fixed intervals according to the general maintenance methodology presented in [52, 104]. The cost of the maintenance activities over the project period is built into the optimization process to make sure the estimation of the economic benefits of the project is accurate, resulting in an optimal retrofit plan that can make full use of an investment.

Although many technologies such as district heating/cooling and solar water heating may reduce the energy consumption of buildings, they do not take into account in the building envelope retrofit under local conditions. For instance, the technology of district heating/cooling, which can be built into the model presented, is not considered because of its unavailability in South Africa. The reason for not considering solar water heating technology is that the majority of water heaters used in local existing buildings are electric geysers, which can be proved by the data from hundreds of measurement and verification projects in South Africa. Therefore, installing PV systems instead of a solar water heating system is favorable owing to its ability of making use of existing water heaters. If one need to considering the above technologies in building retrofit projects, the optimization method proposed in this study is also effective by building the energy consumption/generation of the technologies into the model.

The purpose of the optimization model is to maximize the energy savings and economic benefits of the building envelope retrofit project with a given investment by determining the alternatives for retrofitting the envelope components and the size of the PV power supply system to be installed. The NPV and payback period, which are useful indicators for decision makers to evaluate the profitability of an investment [88, 89], are taken into consideration in the optimization process. These two financial factors can help decision makers to make informed decisions on economical building envelope retrofit plan.

During the optimization process, decision makers need to find the optimal retrofit plan in view of the trade-offs between conflicting objectives [105], namely maximizing energy savings and NPV and minimizing the payback period of the retrofit project. This results in a multiple-objective optimization problem, which can be solved by two approaches, namely Pareto optimization and the weighted sum method. Pareto optimization [92] is based on the concept of dominance. If none of the objectives can

be improved in value without sacrificing at least one other objective in value, the corresponding solution is called non-dominated. The collection of these non-dominated solutions constitutes a Pareto front, which is the solution of the multi-objective optimization problem [106, 107]. Without an additional preference for some objectives, all Pareto optimal solutions are considered to be equally good. In other words, the optimal solutions of the multi-objective problem are a representative set of Pareto optimal solutions, which illustrate the trade-offs among different objectives reasonably according to decision makers' preferences. Finding the complete Pareto front is computationally intense and even impossible in some cases. Even if the complete Pareto front could be found, decision makers have to pick a solution from the Pareto front that best suits their requirements, i.e., the final optimal solution of the multi-objective problem is based on human intelligence. Compared with the Pareto optimization approach, the weighted sum method deals with multi-objective optimization problems in a much easier manner, as it is often used to convert a multi-objective optimization problem into a single-objective optimization problem [108], which is relatively easier to solve. The single-objective optimization function is usually called a 'preference' function or 'utility' function, which is an abstract function without physical meaning in the mind of the decision makers considering the trade-offs between different objectives [109, 110, 111]. Although the weighted sum method cannot guarantee to find the complete Pareto front, it is able to find a solution to the multi-objective optimization problem with a set of weighting factors, which are usually selected carefully according to the trade-offs made among the objectives. That is to say, the weighted sum method provides decision makers or project managers with an effective and convenient method to interface with the solving process of the multi-objective optimization problems to achieve desired solutions by tuning the weighting factors. Therefore, the multi-objective optimization problem for building envelope retrofit planning in this chapter is solved with the weighted sum method.

In summary, this chapter presents an optimization model for a building envelope retrofit, which helps existing building owners to choose the best energy-efficient facilities for retrofit to improve energy efficiency. Modeling of a PV power supply system and the energy balance of a general building is described in Section 2.2. After that, the building retrofit plan is formulated into an optimization problem in Section 2.3. A case study in Section 2.4 is presented to demonstrate the feasibility and effectiveness of the optimization model. Finally, conclusions are drawn in Section 2.5.

## 2.2 SYSTEM MODELING

The energy demand of a general building is the difference between its energy consumption and generation. Therefore, the energy consuming and producing processes of a building must be modeled before the building envelope retrofit problem can be formulated. In the building envelope retrofit project, the energy production for the building results from a rooftop PV power supply system. Hence, the PV system needs to be modeled to determine its contribution to reducing the building's energy demand. As some of the solar panels installed into the PV system will fail over time, the energy producing performance of the system will degrade over the period of the retrofit project. Therefore, the performance degradation of the PV system is modeled to estimate the energy production of the system accurately. In addition, a maintenance strategy for the PV system is designed to ensure the sustainability of the PV system. After that, the energy consuming processes of the building, including energy used by space heating, space cooling and water heating, are modeled.

The size of the rooftop PV system considered to be installed is limited by the effective and usable areas of the building's roof. In particular, it was found that the maximum energy production of the PV system cannot meet the minimum energy demand of the building even though the complete usable area of the building's roof is installed with the best solar panels. Therefore, an energy storage system is not taken into account for the PV system in the building envelope retrofit project studied. This also means that there is no need to consider the installation and maintenance cost of the energy storage system.

### 2.2.1 Degradation model of PV system

The PV power supply system is used to produce electrical energy by converting the solar energy into electricity. It is often believed to be reliable and have a long lifetime, which are reflected by the 25-year power output warranty in the industry [112]. Nevertheless, the performance of energy generation of the PV power supply system degrades inevitably over time because of the population degradation of the solar panels built in the system [113]. To be exact, the effective energy output of the PV system depends on the number of solar panels that are still generating electrical power. Due to the degradation of the PV system on its energy production over time, more cost is needed for the building to purchase the increased power demand from the grid. Subsequently, the sustainable energy savings of the building

retrofit project is influenced by the extra cost. Therefore, investigating the population degradation of the solar panels in the PV system and thereafter taking it into account in the retrofit project are necessary and important. The population degradation model of solar panels can be described with the Weibull distribution, which is considered to be the most popular method of analyzing reliability and life distribution of products. According to the research done in [114], the general form of the population degradation of solar panels can be described by equation (2.1):

$$R_d(t) = e^{-\left(\frac{t}{\varphi}\right)^3}, \quad (2.1)$$

where  $R_d(t)$  represents the survival rate of solar panels at time  $t$  and  $\varphi$  is a scale parameter. With a given  $\mathbb{L}$ , the scale parameter can be calculated by solving equation (2.2) [4, 52]:

$$R_d(\mathbb{L}) = 0.5, \quad (2.2)$$

where  $\mathbb{L}$  is the lifespan of solar panels.

Although there are many factors, such as dust on the glass of solar panels, etc., influencing the power output of the PV system, they are not taken into account in this chapter. This is because these factors are much easier to deal with compared with the failure problem of the solar panels.

Making use of the population degradation model described in equation (2.1), the number of the installed solar panels at the beginning of the retrofit that still work properly at the end of year  $t$ ,  $D(t)$ , can be calculated by equation (2.3):

$$D(t) = N_p^0 R_d(t), \quad (2.3)$$

in which  $N_p^0$  is the number of solar panels installed at the beginning of the retrofit project.

Considering the failure of the solar panels in the PV system, a full maintenance strategy for the system at fixed time intervals is introduced to ensure sustainable energy production. It is described with equation (2.4):

$$M(t) = \begin{cases} N_p^0 - D(t), & \text{if } t = aT_m, \\ 0, & \text{otherwise,} \end{cases} \quad (2.4)$$

where  $M(t)$  is the number of solar panels to be installed in the maintenance activity happening in year  $t$ ,  $a$  is a positive integer and  $T_m$  is the maintenance interval measured in year, which means that a maintenance activity happens every  $T_m$  years. In each maintenance activity, the failed solar panels in the PV system are all replaced together with new ones of the same type, which means that the population size of the solar panels will be restored to the original size,  $N_p^0$ , after each maintenance.



Therefore, the number of solar panels that work properly at the beginning of year  $t + 1$ ,  $N_p(t + 1)$ , can be determined by equation (2.5):

$$N_p(t + 1) = D(t) + M(t). \quad (2.5)$$

### 2.2.2 Energy production of PV system

The energy output of the PV power supply system to be installed depends on the characteristics of the selected solar panels and the number of solar panels installed. The choice of solar panel and number of panels to be installed are determined by the retrofit plan. Taking into account the population degradation model of solar panels and the maintenance strategy for them described in Section 2.2.1, the total energy output of the installed PV power supply system for the building in year  $t$ ,  $E_{pv}(t)$ , can be determined by equation (2.6) [39, 41, 115, 116]:

$$E_{pv}(t) = \sum_{p=1}^P (x_p^{pv} \eta_p) \sum_{p=1}^P (x_p^{pv} A_p^{pv}) I_{pv} \eta_s D(t), \quad (2.6)$$

where  $\eta_p$  is the efficiency of the  $p$ -th solar panel alternative,  $A_p^{pv}$  is the area of one solar panel of the  $p$ -th alternative measured in  $m^2$ ,  $I_{pv}$  is the solar irradiation on the installed PV system measured in  $kWh/m^2$ ,  $\eta_s$  is the average conversion efficiency of solar to electrical power, considering losses due to temperature, dust, etc.  $x_p^{pv}$  denotes the retrofit state of the  $p$ -th solar panel alternative. For instance,  $x_p^{pv} = 1$  indicates that the  $p$ -th alternative is chosen for the PV system installation, while it is not chosen when  $x_p^{pv} = 0$ .

To calculate the energy balance of a general building, the energy production and consumption of the building must be taken into consideration. After modeling the installed rooftop PV power supply system, which is used to produce electricity to reduce the energy demand of the building, the main energy usage of the building must be modeled. The energy consumers of a building mainly include space heating, space cooling and water heating systems, which are described in the following sections.

### 2.2.3 Energy consumption for space heating

The energy consumption for space heating in a general building,  $E_{heat}$ , can be calculated by equation (2.7) [117, 118]:

$$E_{heat} = E_{ext} + E_{enu} - E_{pt} + E_v - E_{gu}, \quad (2.7)$$

in which  $E_{ext}$  is the heat loss through zones in contact with the outdoor environment, including walls, glazing, roofs and pavements, measured in kWh,  $E_{enu}$  is heat loss through zones in contact with non-useful spaces, including walls, glazing, roofs and pavements, measured in kWh,  $E_{pt}$  is heat loss through linear thermal bridges measured in kWh,  $E_v$  is heat loss through fresh air flow measured in kWh and  $E_{gu}$  is useful heat gains measured in kWh.

The values of  $E_{ext}$ ,  $E_{enu}$ ,  $E_{pt}$ ,  $E_v$  and  $E_{gu}$  in equation (2.7) can be obtained by equations (2.8)-(2.12) [9, 117, 119]:

$$E_{ext} = 0.024H_{dd}BLC_{ext}, \quad (2.8)$$

$$E_{enu} = 0.024H_{dd}U_nA_i, \quad (2.9)$$

$$E_{pt} = 0.024H_{dd}\Psi \cdot B, \quad (2.10)$$

$$E_v = 0.024H_{dd}(0.34ACH \cdot A_pP_d), \quad (2.11)$$

$$E_{gu} = \mu \left[ (M_h G_{south} \sum_{i=1}^I x_i^{win} \delta_i \sum_{i=1}^4 Z_i A_{e,i}) + (0.72 A_p M_h \cdot q_i) \right], \quad (2.12)$$

where

$$BLC_{ext} = A_{win}U_{win} + A_{wal}U_{wal} + A_{rof}U_{rof}. \quad (2.13)$$

In equations (2.8)-(2.13),  $H_{dd}$  is the heating degree days measured in °C day.  $BLC_{ext}$  is the building load coefficient measured in  $W/°C$ .  $U_n$  is the thermal transmission coefficient in non-useful space measured in  $W/m^2°C$ .  $A_i$  is the area of non-heated spaces measured in  $m^2$ .  $\Psi$  is linear heat flux transmission measured in  $W/m°C$ .  $B$  is the interior length of the contact between the floor or wall interior linear perimeter and soil or thermal bridge interior length measured in m.  $ACH$  is air changes per hour measured in  $h^{-1}$ .  $A_p$  is the net floor area measured in  $m^2$ .  $P_d$  is the height from floor to ceiling measured in m.  $x_i^{win}$  denotes the state of the  $i$ -th alternative of the windows for the retrofit project, i.e., when  $x_i^{win} = 1$ , it is chosen for the retrofit, while it is not chosen when  $x_i^{win} = 0$ . The same type of variables, such as  $x_j^{wal}$  and  $x_k^{rof}$ , are defined to describe the retrofit states of the wall and roof insulation materials for the retrofit project. They denote whether the  $j$ -th alternative of the external wall insulation materials and the  $k$ -th alternative of the roof insulation materials are chosen for retrofit.  $\mu$  is the heat gains utilization factor.  $M_h$  is the heating season duration measured in months.  $q_i$  is the internal gains measured in  $W/m^2$ .  $G_{south}$  is the average solar energy that reaches a south-oriented vertical surface measured in  $kWh/m^2$ month.  $\delta_i$  is effective solar energy transmittance of the  $i$ -th alternative of the windows.  $Z_i$  is the orientation coefficient for different facades.  $A_e$  is the effective glazing solar radiation collector area for the windows with different orientations measured in  $m^2$ .  $A_{win}$ ,  $A_{wal}$  and  $A_{rof}$  are the surface areas of the windows, exterior walls and roof of the building to be retrofitted, respectively, measured in  $m^2$ .

$U_{win}$ ,  $U_{wal}$  and  $U_{rof}$  are the thermal transmission of the windows, walls and roof of the building after retrofit. They can be obtained by equations (2.14)-(2.16) [118]:

$$U_{win} = \sum_{i=1}^I x_i^{win} U_i, \quad (2.14)$$

$$U_{wal} = \sum_{j=1}^J x_j^{wal} \frac{U_w \lambda_j}{U_w d_j + \lambda_j}, \quad (2.15)$$

$$U_{rof} = \sum_{k=1}^K x_k^{rof} \frac{U_r \lambda_k}{U_r d_k + \lambda_k}. \quad (2.16)$$

In equations (2.14)-(2.16),  $U_i$  is the thermal transmission of the  $i$ -th alternative of the windows measured in  $W/m^2\text{°C}$ ,  $U_w$  and  $U_r$  are the thermal transmittance of the walls and roof of the building before retrofit, respectively, measured in  $W/m^2\text{°C}$ ,  $d_j$  and  $d_k$  are the thickness of the  $j$ -th alternative of the external wall insulation materials and  $k$ -th alternative of the roof insulation materials, respectively, measured in m,  $\lambda_j$  and  $\lambda_k$  are the thermal conductivities of the  $j$ -th alternative of the external wall insulation materials and  $k$ -th alternative of the roof insulation materials, respectively, measured in  $W/m\text{°C}$ .

#### 2.2.4 Energy consumption for space cooling

The energy consumption for space cooling in a general building,  $E_{cool}$ , can be calculated by equation (2.17) [117]:

$$E_{cool} = (1 - \mu)(E_{gu} + E_e + E_t + E_i), \quad (2.17)$$

in which  $E_e$  is the heat gain through the building envelope measured in kWh,  $E_t$  is the heat transfer due to the infiltration of the building, and  $E_i$  is internal heat gains of the building measured in kWh.

The values of  $E_e$ ,  $E_t$  and  $E_i$  in equation (2.17) can be obtained by equations(2.18)-(2.20) [117]:

$$E_e = BLC_{ext} \left[ 2.928(\theta_m - 25) + \left( \alpha \frac{I_r}{25} \right) \right], \quad (2.18)$$

$$E_t = 2.928(0.34ACH \cdot A_p P_d)(\theta_m - 25), \quad (2.19)$$

$$E_i = 2.928A_p \cdot q_i. \quad (2.20)$$

In equations (2.18)-(2.20),  $\theta_m$  is the average outdoor temperature in the cooling season measured in  $\text{°C}$ ,  $\alpha$  is the exterior envelope solar radiation absorption coefficient,  $I_r$  the is average solar radiation measured in  $\text{kWh/m}^2$ .

### 2.2.5 Energy consumption for water heating

The energy consumption for water heating in a general building,  $E_{water}$ , can be calculated by equation (2.21) [117]:

$$E_{water} = 0.081M_a \frac{n_d}{\eta_a}, \quad (2.21)$$

where  $M_a$  is the average daily water consumption measured in kWh,  $n_d$  is the number of days when domestic water heating occurs,  $\eta_a$  is the domestic water heating system efficiency.

## 2.3 OPTIMIZATION

The aim of this study is to determine an optimal envelope retrofit plan considering maintenance for a building for energy efficiency improvement. The retrofit plan is formulated into a multiple-objective optimization problem, the goal of which is to maximize the energy savings and financial benefits of the retrofit project. The optimization problem can be described in the following format:

$$\begin{aligned} &\mathbf{max} && \text{energy savings, and NPV} \\ &\mathbf{min} && \text{payback period} \\ &\mathbf{s.t.} && \text{budget available, and effective rooftop area.} \end{aligned} \quad (2.22)$$

### 2.3.1 Decision variables

In this study, the building envelope retrofit actions consist of two parts, including replacing existing windows with better ones and installing insulation materials on the walls and roof. In addition, a rooftop PV power supply system is taken into consideration in the optimization process of the building envelope retrofit problem. Therefore, assume that there are  $I$  alternatives of windows,  $J$  alternatives of wall insulation materials and  $K$  alternatives of roof insulation materials for the building envelope retrofit and  $P$  alternatives of solar panels available for the installation of a PV system.

Let

$$\begin{aligned} X_{win} &= [x_1^{win}, \dots, x_I^{win}], \\ X_{wal} &= [x_1^{wal}, \dots, x_J^{wal}], \\ X_{rof} &= [x_1^{rof}, \dots, x_K^{rof}], \\ X_{pv} &= [x_1^{pv}, \dots, x_P^{pv}]. \end{aligned}$$

The decision variable of the retrofit planning problem is then given by:

$$X = [X_{win}, X_{wal}, X_{rof}, X_{pv}, N_p^0].$$

### 2.3.2 Objectives

The objectives of the optimization problem are to maximize energy savings and economic benefits (evaluated by NPV and the payback period). Indicators of these objectives are mathematically determined as below.

The total energy savings of the building envelope retrofit project considering maintenance is the difference between the energy consumed by the building before the retrofit and that after the retrofit over a time period  $[0, T]$ . It can be calculated by summing up the energy savings of each year in the  $T$  years period. The model to calculate the total energy savings after the retrofit considering facility performance degradation over time and maintenance actions during the period  $[0, T]$ ,  $ES_{tot}$ , is described by equation (2.23):

$$ES_{tot} = E_{pre} - E_{post} = \sum_{t=1}^T ES(t), \quad (2.23)$$

where  $E_{pre}$  and  $E_{post}$  are the total energy consumption of the building before and after the envelope retrofit in the time period  $[0, T]$ , respectively, measured in Wh,  $ES(t)$  is the energy savings of year  $t$  measured in Wh. The formula used to calculate the value of  $ES(t)$  is described by equation (2.24):

$$ES(t) = \Delta E_{heat}(t) + \Delta E_{cool}(t) + \Delta E_{water}(t) + E_{pv}(t). \quad (2.24)$$

In equation (2.24),  $\Delta E_{heat}(t)$ ,  $\Delta E_{cool}(t)$  and  $\Delta E_{water}(t)$  are the difference of the energy consumptions before and after the retrofit for space heating, space cooling and water heating of the building, respectively, in year  $t$  measured in Wh.

Net present value (NPV) is the present value of an investment project's expected cash inflows minus its cash outflows over a period of time. It is a popular method used in capital budgeting which accounts for the time value of money to analyze the profitability of an investment. A positive net present value represents that the investment will be a profitable one. Otherwise, the investments with negative NPV values will result in a net loss. That is to say, only the projects with positive NPV values are worthy of investments. A higher NPV value indicates that the investment is more profitable. Therefore, NPV is an important indicator for decision makers to determine an investment. In this study, the NPV method

is adopted to evaluate the profitability of the building envelope retrofit plan considering maintenance. With the discount rate,  $d$ , the NPV of the retrofit project can be determined by equation (2.25):

$$NPV = \sum_{t=1}^T \frac{ES(t)p(t) - C_m(t)}{(1+d)^t} - C_r, \quad (2.25)$$

where

$$C_m(t) = M(t) \sum_{p=1}^P x_p^{pv} C_{m_p}^{pv}, \quad (2.26)$$

$$C_r = A_{win} \sum_{i=1}^I x_i^{win} C_i^{win} + A_{wal} \sum_{j=1}^J x_j^{wal} C_j^{wal} + A_{rof} \sum_{k=1}^K x_k^{rof} C_k^{rof} + N_p^0 \sum_{p=1}^P x_p^{pv} C_p^{pv}. \quad (2.27)$$

In equations (2.25)-(2.27),  $p(t)$  is the electricity price in year  $t$  measured in \$/Wh,  $C_m(t)$  is the maintenance cost for the solar panel power supply system in the  $t$ -th year measured in \$,  $C_r$  is the cost of building envelope retrofit measured in \$,  $d$  is the discount rate,  $C_i^{win}$  is the cost of the  $i$ -th alternative of the windows for retrofit measured in \$/m<sup>2</sup>,  $C_j^{wal}$  is the cost of the  $j$ -th alternative of the external wall insulation materials for retrofit measured in \$/m<sup>2</sup>,  $C_k^{rof}$  is the  $k$ -th alternative of the roof insulation materials for retrofit measured in \$/m<sup>2</sup>,  $C_p^{pv}$  is the unit cost of the  $p$ -th alternative of the solar panels measured in \$,  $C_{m_p}^{pv}$  is the unit maintenance cost of the  $p$ -th type solar panel measured in \$,  $A_p^{pv}$  is area of the  $p$ -th alternative of the solar panels measured in m<sup>2</sup>. From equation (2.25) and (2.26), it can be observed that this formulation explicitly builds the maintenance cost of the project into the optimization problem, which yields more accurate estimation of the project cost and performance during the evaluation period.

In addition to the NPV indicator used to evaluate the profitability of an investment, another important indicator, the payback period, is taken into account, as it is usually used to reflect how quickly an investment can recover its capital cost, taking the discount of cash flow into consideration. The payback period factor is helpful for decision makers having to make informed decisions when comparing different investment projects.

The payback period is defined as the time point after which the value of NPV of an investment becomes positive. Based on the definition, the payback period of the building envelope retrofit project considering maintenance, taking into account the discounts of cash flow, can be determined by equation (2.28):

$$T_p = M + \frac{|\bar{C}_f(M)|}{C_f(M+1)}, \quad (2.28)$$

where  $T_p$  is the payback period measured in months,  $M$  is the last month in which a negative cumulative discounted cash flow occurs after the investment,  $|\bar{C}_f(M)|$  is the absolute value of the cumulative cash

flow at the end of the  $M$ -th month measured in \$,  $C_f(M + 1)$  is the total discounted cash flow during the  $(M + 1)$ -th month measured in \$.

As mentioned above, a multi-objective optimization problem for building envelope retrofit projects can be formulated. With the weighted sum method introduced in Section 2.1, the multiple-objective optimization problem can be converted into a single-objective optimization problem, which can be described with the objective function (2.29):

$$J = -w_1 \frac{ES_{tot}}{\overline{ES_{tot}}} - w_2 \frac{NPV}{\overline{NPV}} + w_3 \frac{T_p}{\overline{T_p}}, \quad (2.29)$$

where  $w_1$ ,  $w_2$  and  $w_3$  are positive weights. In equation (2.29),  $\overline{ES_{tot}}$ ,  $\overline{NPV}$  and  $\overline{T_p}$  are the maximum values of the  $ES_{tot}$ ,  $NPV$  and  $T_p$ , respectively. They are used to standardize the three terms in the objective function for the convenience of the weighting factors tuning.

### 2.3.3 Constraints

The constraints of the optimization problem include two parts, including the budget limit and physical limit.

The budget limit for the project of the building envelope retrofit considering maintenance can be described by

$$C_{tot} \leq \beta, \quad (2.30)$$

where  $C_{tot}$  is the total cost of the building envelope retrofit considering maintenance during a time period  $[0, T]$  measured in \$, and  $\beta$  is the budget allocated to the project measured in \$. The value of  $C_{tot}$  can be determined by equation (2.31):

$$C_{tot} = C_r + \sum_{t=1}^T C_m(t). \quad (2.31)$$

The physical limits of the building envelope retrofit project are twofold, including the limited installation area for the PV power supply system on the roof of the building and the decision variables' boundary limits.

The area limit, which implies that the size of the PV power supply system to be installed should be less than the effective and usable area of the roof, is described by

$$\sum_{p=1}^P x_p^{pv} A_p^{pv} N_p^0 \leq A_{eff}, \quad (2.32)$$

where  $A_{eff}$  is the usable area of the roof for the PV system installation measured in  $m^2$ .

The design limits on the decision variables, which are to ensure that only one alternative for each retrofit category is chosen by the retrofit plan, are described by

$$\begin{cases} \sum_{i=1}^I x_i^{win} = 1 & \text{for } x_i^{win} \in \{0, 1\}, \forall i \in \{1, 2, \dots, I\} \\ \sum_{j=1}^J x_j^{wal} = 1 & \text{for } x_j^{wal} \in \{0, 1\}, \forall j \in \{1, 2, \dots, J\} \\ \sum_{k=1}^K x_k^{rof} = 1 & \text{for } x_k^{rof} \in \{0, 1\}, \forall k \in \{1, 2, \dots, K\} \\ \sum_{p=1}^P x_p^{pv} = 1 & \text{for } x_p^{pv} \in \{0, 1\}, \forall p \in \{1, 2, \dots, P\}. \end{cases} \quad (2.33)$$

## 2.4 CASE STUDY

### 2.4.1 Case information

In this part, an existing building is used as a case study to demonstrate the viability of the optimization model for the building envelope retrofit planning. The building is a residential building constructed in the 1960s in South Africa. It faces southeast and consists of 66 apartments. The structure of each apartment is the same, with an open kitchen, a small bathroom, one living room and two bedrooms, as shown in Fig. 2.1. The gross area of an apartment of the building is  $70 \text{ m}^2$  and the glazing area is  $13.3 \text{ m}^2$ , of which  $10.6 \text{ m}^2$  faces north and  $2.7 \text{ m}^2$  faces south. The climate zone of the building is 2 and the weather information of the climate zone is from South Africa Weather Bureau.

The windows of the existing building are standard single glazing ones with wood frames and the roof, walls and floor have no thermal insulation. In the retrofit plan for the building, it is considered to retrofit the windows with more energy-efficient alternatives and to install insulation materials on the roof and walls in order to improve the energy performance of the building. In addition, building a PV power supply system is taken into account to reduce the energy demand of the building from the grid. The detailed information of the facilities used in the retrofit project, including windows, insulation materials





**Figure 2.1.** Structure of an apartment in the building under study

**Table 2.1.** Parameters of windows

<i>i</i>	Description	$U_i$ (W/m <sup>2</sup> °C)	$\delta_i$ (%)	$C_i^{win}$ (\$/m <sup>2</sup> )
1	Single glazing, typical glazing	5.1	85	43.91
2	Double glazing, without thermal break, uncoated air-filled metallic frame 4-12-4	2.8	75	50.79
3	Double glazing, without thermal break, uncoated air-filled metallic frame 4-16-4	2.7	75	51.94
4	Double glazing, low-e window (with thermal break) coated air-filled metallic frame 4-12-4 NEUTRALUX	1.6	62	71.79
5	Double glazing, window air-filled metallic frame 6-12-4 SOLARLUX Supernatural 70/40 Temprado	1.6	44	174.62

**Table 2.2.** Parameters of external wall insulation materials

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

for walls and roof and solar panels, are provided in Tables 2.1-2.4. In Table 2.2-2.3, the abbreviations EPS and SPF stand for expanded polystyrene and sprayed polyurethane foam, respectively.

**Table 2.3.** Parameters of roof insulation materials

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

**Table 2.4.** Parameters of solar panels

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

In view of the performance degradation of the PV power supply system, a full maintenance strategy is developed based on the degradation model of solar panels mentioned in Section 2.2.1. According to the model, around 20% of the solar panels in the PV system will fail in six years after the retrofit. Therefore, the maintenance strategy in this study determines that maintenance of the PV system occurs every six years to repair the energy generation ability of the system. In particular, the solar panels that fail to work properly in the PV system are replaced with new ones when maintenance is done.

In this study, the project period is 24 years. The baseline energy consumption of the existing building before the implementation of the retrofit plan is 766.32 MWh per year. The increase rate of the electricity price in South Africa is determined as 8%, according to the published increase rate of electricity from Eskom, which is the only utility in South Africa. The discount rate related to the calculation of NPV is set at 9% [90]. The temperature set points of the HVAC system of the apartments in the building are 20°C in heating seasons and 25°C in cooling seasons.

### 2.4.2 Algorithm selection

Because the retrofit problem formulated is a mixed integer nonlinear programming problem, traditional calculus based techniques cannot be used to find solutions to this problem. Modern optimization techniques, therefore, must be employed for this purpose. There are several types of algorithms developed since 1940s, including evolution based algorithms, simulated annealing, swarm intelligence algorithms, neural-network based optimization, and fuzzy optimization techniques [120, 121]. Given

the wide variety of modern optimization techniques available, choosing the right one from them is a challenging task [122] because the performance of all these algorithms are problem-specific and there is no general guideline for picking the right one for a given problem as concluded in the ‘no free lunch theorems for optimization’ by D. H. Wolpert and W. G. Macready [123].

In view that the problem to be solved is a nonlinear mixed integer one, the literature has been consulted and it was found that genetic algorithm is the one that was tested to be a better option to solve such type of problems in several articles, for example [91, 98, 124, 125]. It was further reported that a binary coded genetic algorithm is more efficient in solving NMIP problems than real coded ones [126, 127]. Therefore, a binary coded genetic algorithm is chosen to solve the building retrofit problems formulated in this thesis.

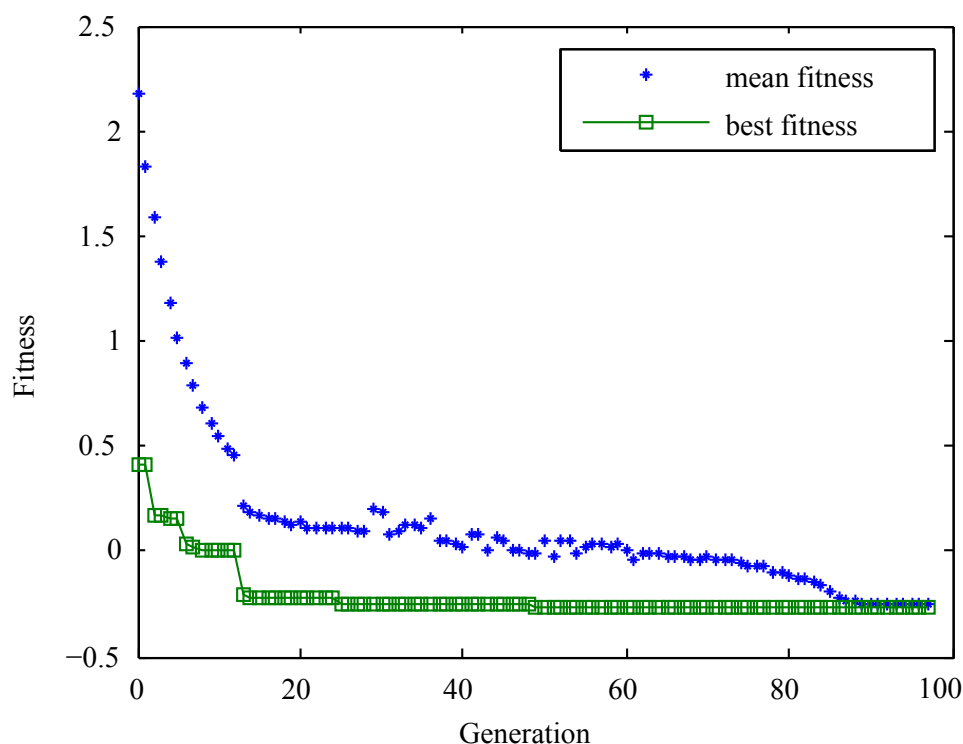
### 2.4.3 Results with GA

In this study, a genetic algorithm (GA) is employed to solve the optimization problem [128, 129]. The initial population size and the crossover probability in the GA are set to 2000 and 0.8, respectively. In addition, the algorithm is set to terminate when the change of the best fitness is less than  $1 \times 10^{-10}$ . Fig. 2.2 is provided to show that the convergence of the GA algorithm has been achieved within acceptable numbers of generations. It can be seen that the fitness of the best individual and the average fitness of all individuals in a generation continuously decrease. In particular, the fitness of the best individual converges to a fixed value, which ensures that the solution to the building retrofit project found by the GA algorithm is a local optimum at least. Essentially, no mathematical method and artificial intelligence method can guarantee convergence to the global optimum in view of the characteristics of the formulated problem, i.e., a mixed-integer nonlinear programming problem.

In the rest of the thesis, the building retrofit and maintenance plans obtained by the optimization models proposed are sub-optimal solutions at least.

### 2.4.4 Results with $w_1 = 0.7$ , $w_2 = 0.2$ and $w_3 = 0.1$

To strike a balance among the three objectives, including energy savings, NPV and payback period, in the objective function of the building envelope retrofit project, the corresponding weighting factors



**Figure 2.2.** Convergence of the GA algorithm

are set to  $w_1 = 0.7$ ,  $w_2 = 0.2$  and  $w_3 = 0.1$  during the optimization process. In order to investigate the impact of different investments on the optimal retrofit plan, the optimal solutions for the retrofit project with different budgets achieved by the optimization model are detailed in Table 2.5.

In Table 2.5, window, wall, roof and solar represent the corresponding retrofit components in the building envelope retrofit project and  $N_p^0$  represents the number of solar panels installed at the beginning of the retrofit. The optimal retrofit actions on these corresponding facilities of the building with different budgets are indicated by the numbers in the last five columns of the table. For instance, the combination of the numbers ‘1, 5, 7, 2, 84’ in the last five columns of the fourth row indicates that the best retrofit plan for the building with a budget of \$14000 is to replace the existing windows with the first alternative of the windows listed in Table 2.1, apply the walls and roof with the fifth alternative of the external wall insulation materials listed in Table 2.2 and the seventh alternative of roof insulation materials listed in Table 2.3 and build the PV system with 84 of the fifth alternative of the solar panels listed in Table 2.4. It can be found from Table 2.5 that the optimal retrofit plans for the existing building varies depending on the investments. In particular, the optimal retrofit plan does not simply choose the most expensive ones of the alternatives for the retrofit. For instance, the optimal retrofit solution is ‘1, 5, 3,

**Table 2.5.** Results with  $w_1 = 0.7$ ,  $w_2 = 0.2$  and  $w_3 = 0.1$

$\beta$ (\$)	$C_{tot}$ (\$)	$ES_{tot}$ (kWh)	$ES_p$ (%)	NPV (\$)	$T_p$ (month)	Window	Wall	Roof	Solar	$N_p^0$
80000	79663	6795741	36.95%	732773	27	1	5	3	5	9
100000	98224	7036293	38.25%	742719	32	1	6	6	2	11
120000	119296	7259845	39.47%	747241	38	4	11	7	2	4
140000	134273	7504273	40.80%	766817	39	1	5	7	2	84
160000	158078	7634215	41.50%	759610	45	1	6	6	2	97
180000	179511	7750310	42.14%	755262	49	3	5	7	2	138
200000	198594	8099689	44.04%	778461	52	4	5	4	5	125

5, 9' with a budget of \$80000 while the solution with a budget of \$100000 is totally different, which is '4, 11, 7, 2, 4'.

In Table 2.5, the results of the retrofit plan in terms of energy savings are given by the items  $ES_{tot}$  and  $ES_p$ , which represent the total energy savings of the retrofit project and the percentage of energy savings comparing with the baseline energy consumption of the building. The impact of the retrofit plan in terms of economic benefits is also described with the items NPV and  $T_p$ . For instance, 679.6 MWh (36.95%) of energy can be saved and \$732773 NPV can be achieved in the project period with a budget of \$80000, the payback period of which is 27 months. It can be seen from the table that energy and economic items mentioned above vary according to changes in investments,  $\beta$ . With increasing investments, the energy savings and payback period of the project keep growing while the NPV and the number of the solar panels built into the PV system at the beginning fluctuate. When comparing the total costs of the retrofit project,  $C_{tot}$ , with the investments, one can found that the investments are almost exhausted to achieve energy savings and economic benefits.

It can be found that the retrofit options are the same while the size of the PV system grows from 11 to 97, which results in 3.25% extra energy savings when the investment grows from \$100000 to \$160000. This is in line with the statement mentioned in Section 2.1 that installing PV systems is a feasible method to reduce the energy demand of buildings due to the rich solar resource in South Africa. When the budget of the retrofit project is set to \$80000, only nine solar panels are installed at the beginning. However, 36.95% energy can be saved. The result validates that improving the energy performance of buildings by envelope retrofit is an effective method to reduce their energy consumption.

Table 2.5 shows an interesting phenomenon: the number of installed solar panels determined by the optimal retrofit plan decreases from 11 to 4 when the budget increases from \$100000 to \$120000. To explain this ‘abnormality’, one can calculate that if the optimal retrofit options of the alternatives for the windows, walls, roof and PV system with a budget of \$100000, which is the combination of the first alternative of the windows, the sixth alternative of the wall insulation materials, the sixth alternative of the roof insulation materials and the second alternative of the solar panels, is still used in the case of a \$120000 budget, the extra \$20000 would allow 41 solar panels to be installed instead of four. That is to say, the solution in this situation is ‘1, 6, 6, 2, 41’, which leads to total energy savings of 724.5 MWh, less than 726.0 MWh, which is achieved by the optimal plan with the budget of \$120000. Since the weighting factors in the objective function,  $w_1$ ,  $w_2$  and  $w_3$ , are tuned during the optimization process so that the solutions obtained favor more energy savings, simply increasing the number of installed PV panels while keeping the retrofit options for the facilities in the building unchanged would result in an inferior retrofit plan when the investment increases. This illustrates the effectiveness and necessity of the presented optimization model to search for the optimal retrofit solution for a building with various investments. In addition, this demonstrates that the investment may not be used optimally with intuitive retrofit plans. Therefore, the optimization model provides a useful tool for decision makers to work out an optimal retrofit plan for building envelope retrofit projects with various investments.

A similar phenomenon occurs when the investment increases from \$180000 to \$200000 in Table 2.5. Combined with the analysis above, it can be observed that the optimal retrofit plans would rather improve the energy efficiency of the building by retrofitting the envelope components instead of installing solar panels when the investment is not enough to retrofit the envelope components with the best alternatives. Therefore, the first priority should be to improve the energy performance of buildings’ envelopes in the investigation of energy-efficient building retrofit problems in an attempt to maximize the building’s energy savings.

#### 2.4.5 Results with $w_1 = 0.1$ , $w_2 = 0.2$ and $w_3 = 0.7$

In order to investigate the influence of tuning the weighting factors in the objective function of the building envelope retrofit project on the optimal retrofit plans, a set of optimal results with different weighting factors is obtained and presented in Table 2.6. The weighting factors are set to  $w_1 = 0.1$ ,  $w_2 = 0.2$  and  $w_3 = 0.7$ , in which  $w_1$  is set to a smaller value while  $w_3$  is set to a larger value compared

**Table 2.6.** Results with  $w_1 = 0.1$ ,  $w_2 = 0.2$  and  $w_3 = 0.7$

$\beta$ (\$)	$C_{tot}$ (\$)	$ES_{tot}$ (kWh)	$ES_{tot}$ (%)	NPV (\$)	$T_p$ (month)	Win	Wall	Roof	Solar	$N_p^0$
80000	74472	6693658	36.39%	724485	26	1	8	7	2	6
100000	81114	6791717	36.92%	731201	27	1	5	3	1	8
120000	116070	7031982	38.23%	726409	37	2	5	5	4	37
140000	122515	7170607	38.98%	737208	38	3	5	5	5	52
160000	151036	7288412	39.62%	726465	44	2	5	4	2	103
180000	165476	7697435	41.85%	757609	48	1	12	6	2	63
200000	189586	7848263	42.67%	757968	51	3	5	7	2	152

with the weighting factors applied in Section 2.4.4, to obtain optimal solutions that favor minimizing the payback period rather than maximizing the energy savings of the retrofit project. In the optimization process, the budgets are set to be the same as those used in Table 2.5 for the convenience of comparing the results between Tables 2.5 and 2.6.

It can be observed that the results in Table 2.6 validate many conclusions from Table 2.5. For instance, the optimal retrofit plans and their resulting energy savings and economic benefits vary depending on the investments. The energy savings and payback period of the building envelope retrofit project keep growing while the NPV and the number of solar panels built into the PV system at the beginning of the retrofit fluctuate when the investment for the project keeps growing. The optimal retrofit plan with a budget of \$80000 illustrates the effectiveness of improving the energy efficiency of the building by retrofitting its envelope.

The effectiveness of the corresponding weighting factors of energy savings, NPV and the payback period can be verified by comparing the results presented in Table 2.5 and Table 2.6. One can see that the payback period is shorter and the energy savings are lower in Table 2.5 compared to the corresponding values shown in Table 2.6 with the same budgets. For example, the payback period and energy savings in Table 2.6 are 3.7% and 1.5% less than those in Table 2.5 with the budget of \$80000, respectively. This is because the weighting factors in Section 2.4.4 favor solutions that prioritize energy savings maximization, while the weighting factors in Section 2.4.5 favor solutions that prioritize payback period minimization. This can also explain why the investments are almost exhausted in Table 2.5 while they are not in Table 2.6.



In Table 2.6, an interesting phenomenon occurs when the investment grows from \$160000 to \$180000. The retrofit options for the envelope components are changed while the number of installed solar panels decreases from 103 to 63. One can work out why this happens by applying the optimal retrofit plan with a budget of \$160000 (the first alternative of the windows, the eighth alternative of the wall insulation materials, the seventh alternative of the roof insulation materials and the second alternative of the solar panels) to the case of the \$180000 budget and the extra funds are all used for installing solar panels. The corresponding retrofit plan will result in a payback period of 50 months, which is two months longer than that of the optimal retrofit plan obtained by the optimization model with the budget of \$180000. This validates the view in Section 2.4.4 that an inferior solution will be obtained if one simply increases the number of solar panels according to intuition when the investment increases.

Based on this finding and the weighting analysis, one can conclude that improving the energy performance of the envelopes of buildings should be taken into consideration preferentially in an energy-efficient building retrofit plan when the retrofit project is well funded and PV system installation is a feasible way to reduce the energy consumption of buildings in view of the adequate solar resource in South Africa. In addition, the optimization model presented in this chapter provides great help for decision makers in obtaining the optimal retrofit plans according to the preferences given to the performance indicators of the projects, especially when the budget of the project is limited. By applying an optimal building envelope retrofit plan, considerable energy savings and a relatively short payback period of the project can be achieved.

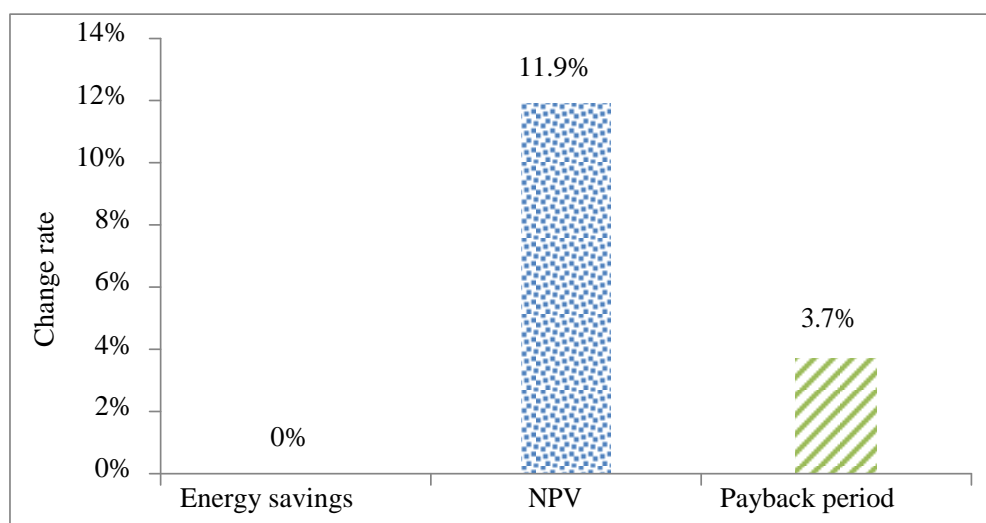
In the case under study, it is observed that the maximum peak power output of the rooftop PV power supply system installed according to the optimal retrofit plans is 16.8 kW, which is less than the measured minimum energy demand of the existing building, 57 kW. Therefore, the installation of an energy storage system for the PV system need not be taken into consideration in this study, which validates the assumption made at the beginning of Section 2.2.

#### **2.4.6 Sensitivity analysis**

In practice, there is a discrepancy between the actual performance and the estimations of a project because of the inaccuracies of the parameters. Therefore, a sensitivity analysis should be performed

for these kinds of parameters to investigate the influence of the bias on the parameters. In particular, the discount rate in this case study, which is recommended to be 9% in [90], could vary because of the fluctuation in the economy. Hence, a 10% decrease in the recommended discount rate is introduced, resulting in a discount rate of 8.1%. Then the new discount rate is applied and simulated with a budget of \$80000.

The results of the sensitivity analysis, which show the performance bias on the indicators of the retrofit project, including energy savings, NPV and the payback period, are detailed in Fig. 2.3. To be specific, the optimal solution to the building envelope retrofit problem did not change, thus leading to a change rate of 0% in the energy savings obtained. However, the decreased discount rate affects the NPV and payback period. In Fig. 2.3, it can be seen that the NPV grows from \$732773 to \$820093 (increases by 11.9%) and the payback period reduces from 27 to 26 months (decreases by 3.7%).



**Figure 2.3.** Sensitivity analysis of the discount rate

According to the sensitivity analysis performed for the discount rate, one can conclude that the energy savings obtained by the optimization mode are robust against the uncertainty about the discount rate, while the economic indicators, such as NPV and the payback period, are sensitive to the change in the discount rate.

To sum up, the results of applying the optimal retrofit plan to the existing building under study demonstrate the viability and effectiveness of the proposed optimization model in improving the

energy performance of existing buildings with a given investment. Moreover, the results provide explicit indicators, such as energy savings, NPV and the payback period, which are very important for decision makers and potential investors. In particular, the discounted rate and the increase rate of the electricity price in South Africa are taken into account when calculating the energy and economic indicators during the optimization process. This can lead to an accurate estimation of the performance of investment projects, which is of great help for decision makers to make a more informed decision. In addition, the results obtained by the optimal retrofit plan are very helpful to overcome the hesitation of decision makers and potential investors and attract more investment for similar building retrofit projects. More importantly, the optimization model presented in this chapter provides decision makers with a convenient method to achieve a desired building retrofit plan that matches their preferences for certain performance indicators by tuning the weighting factors.

For a given building envelope retrofit project, the optimization model can be adopted to determine suitable retrofit actions, which are to improve the energy efficiency of the building after an energy audit of the building. The parameters of the existing technologies, including the thermal performance, cost and similar considerations, as well as those of the identified suitable retrofit options, can be included in the proposed model to compile an optimal envelope retrofit plan for the existing building according to decision makers' preferences, which are emphasized by the weighting factors.

## 2.5 CONCLUSION

A optimization model for building envelope retrofit planning is introduced in this chapter. The purpose of the optimization problem is to promote the energy performance of existing buildings and maximize the energy savings and financial benefits of the retrofit projects with a given budget. The retrofit actions for existing buildings consist of replacing windows with better alternatives, installing insulation materials on the walls and roof and building a PV power supply system. During the optimization process, the performance degradation of the PV system and the corresponding maintenance strategy designed for it are taken into consideration in order to achieve an accurate estimation of the energy savings and financial benefits of the retrofit projects. To calculate the financial benefits, factors such as NPV and the payback period, which are critical for decision makers to determine the feasibility of investments in building envelope retrofit projects, are taken into consideration. The optimization model gives decision makers an effective and convenient method to interface with the optimization

and achieve the desired optimal building envelope retrofit plans by tuning the weighting factors, which are used to give prominence to certain performance indicators. The results of a case study show that a retrofit project can achieve promising energy and financial benefits by applying the optimal retrofit plan obtained to the building. In addition to that, it can be concluded that the retrofit priority should be given to the envelope components instead of the PV system if the available investments are sufficient.

# **CHAPTER 3 BUILDING RETROFIT PLANNING FOR EPC COMPLIANCE**

## **3.1 INTRODUCTION**

As mentioned in Chapter 2, retrofitting existing buildings is a priority method to reduce the high energy demand of the building sector. For the purpose of making existing buildings ‘greener’, the government of South Africa has developed a national regulation on reducing the energy consumption of buildings, which is the EPC for buildings [7] that is used to rate the energy efficiency of buildings. The EPC standard is mandatory once it is implemented. To reach the requirements of the EPC rating system, the owners or managers of existing buildings have to upgrade their buildings by implementing energy-efficient interventions to reduce their energy consumption, as most of these buildings were constructed many years ago without considering energy efficiency. This rating system is similar to the green building rating systems in other countries, such as the LEED standard developed by the US Green Building Council (USGBC) and the Green Star rating system from Australia. The difference is that the EPC rating system only concentrates on the energy intensity of buildings without taking into account other factors, such as indoor air quality and water efficiency.

The EPC rating system is proposed to be implemented first in public buildings, and will then be applied to all types of buildings at a later stage. According to the energy intensity of buildings, which is defined as the annual net energy consumption of a building in kilowatt hours per square meter, the rating system classifies the energy performance of a building into seven grades ranging from grade A to grade G. Grade A is for buildings that are most energy-efficient and grade G is for the ones that are most energy-inefficient. The rating level of a general building can be determined by comparing the energy intensity of that building to a reference value, which varies with the occupancies and

climate zones of the buildings listed in the standard SANS 10400-XA [130]. The green building policy published by the government requests that all the buildings owned or occupied by the public sector must obtain a rating of at least grade D from the EPC to be in compliance with the policy. Although the minimum requirement for target buildings is grade D from the EPC, the government of South Africa develops some programs to encourage buildings to pursue a higher rating. For instance, the tax incentive program <sup>1</sup> introduced under the section 12L of the Income Tax Act is one of these programs. It encourages building owners to reduce the energy consumption of their buildings by allowing them to claim a deduction of their taxable income according to the energy savings over a year comparing to the baseline consumption in the previous year. The 12L tax incentive helps to bring in an additional cash flow by means of reduced tax paid by the building owner, which can be used to shorten the payback period of the retrofit project.

The energy consumption of a general building can be attributed to its envelope and indoor appliances. In the literature, these two subsystems were studied separately [4, 42, 95]. No study on a systematic retrofit plan for the whole building, including both the envelope system and the indoor system, has been reported so far. In addition, a systematic whole-building retrofit plan taking into account the green building policy, which in South Africa is the EPC rating system, is urgently needed to help decision makers to ensure that the retrofit is financially beneficial and the resulting building complies with the green building policy requirements. This has not been investigated in the literature.

Therefore, this paper fills the above-mentioned gap and presents an optimization model that can determine a systematic optimal retrofit plan for the whole building, considering both the envelope system and indoor systems, aimed at maximizing the energy savings of the building retrofit project and achieving a desired rating from the EPC rating system to comply with the green building policy in the most cost-effective way. In addition, the proposed model treats the retrofit plan as a multi-year project with improving efficiency targets in consecutive years for the building. This is considered because retrofitting a building to obtain the best rating (grade A) usually requires a significant amount of investment with a long payback period, which makes building retrofit projects unattractive to decision makers or potential investors. Moreover, the economic situation of South Africa has been vulnerable in recent years. Therefore, the proposed optimization method of breaking the once-off long-term project up into smaller projects with relative shorter payback periods is helpful to overcome the hesitation of decision makers or potential investors and even to attract more investments to similar building retrofit

---

<sup>1</sup><http://www.sanedi.org.za/12L.html>

projects. In order to reduce the payback period of building retrofit projects further, the tax incentive program is also taken into consideration in this study.

The optimization problem is again solved with the weighted sum method. Therefore, decision makers can obtain a desired optimal retrofit solution by tuning the weighting factors of the critical indicators of an investment, including energy savings and the payback period, according to their preferences.

The remainder of this chapter includes four parts. Details of the modeling process, including the energy consumption of a building and energy production of a PV power supply system, are described in Section 3.2. Formulation of the building retrofit problem is presented in Section 3.3. After that, a case study with results analysis is provided in Section 3.4 to validate the feasibility of the proposed model. A conclusion is drawn in Section 3.5.

## **3.2 SYSTEM MODELING**

The energy consuming process is modeled first, including the energy used by the cooling and heating load and the energy consumed by the indoor lighting system and appliances of the building. Because of the sufficient solar resource and the unavailability of other technologies such as the district heating/cooling system in South Africa, a PV power supply system is introduced into the retrofit project. Therefore, the energy produced by the PV system for the building is modeled.

In the following subsections, equations for calculating the cooling and heating loads of a building are derived from [9, 119] if not specifically stated otherwise.

### **3.2.1 Energy consumed by cooling load**

The cooling load is the amount of heat energy that needs to be removed from a space by the HVAC system to maintain the air temperature of the space at a designed level. The factors that may influence the cooling load of a general building mainly include the envelope components, air leakage, operation of the lights and appliances and occupants. Therefore, to calculate the total energy consumption of the cooling load in a building, these factors must be taken into consideration. During the calculations, the factors affecting the cooling load can be divided into four parts, including transmission heat

gain, infiltration and ventilation heat gain, solar heat gain and internal heat gain, by which the energy consumed is modeled in the following subsections.

The transmission heat gain of a general building through its envelope components, such as the windows, walls, roof, floor, etc., is determined by the heat transfer coefficient, the U-value, which is used to describe the ability of heat conduction of the components. Hence, the transmission heat gain of the cooling load in year  $t$ ,  $E_{tc}(t)$ , can be obtained by equation (3.1):

$$E_{tc}(t) = C_{dd}(t)(A_{win}U_{win}(t) + A_{wal}U_{wal}(t) + A_{rof}U_{rof}(t) + A_{flr}U_{flr}(t)), \quad (3.1)$$

where  $C_{dd}(t)$  is the cooling degree days in year  $t$  measured in  $^{\circ}\text{Ch}$ ,  $U_{win}(t)$ ,  $U_{wal}(t)$ ,  $U_{rof}(t)$  and  $U_{flr}(t)$  are the thermal transmittances of the windows, walls, roof and floor of the building in year  $t$ , respectively, measured in  $\text{W}/\text{m}^2\text{C}$ . As the floor of the building is not considered to be retrofitted in this paper, the thermal transmittance of the floor,  $U_{flr}(t)$ , remains unchanged. The thermal transmittances of other building envelope components will change when they are retrofitted. Their values after retrofit can be calculated by equations (3.2)-(3.4):

$$U_{win}(t) = \sum_{i=1}^I x_i^{win}(t)U_i, \quad (3.2)$$

$$U_{wal}(t) = \sum_{j=1}^J x_j^{wal}(t) \frac{U_w \lambda_j}{U_w d_j + \lambda_j}, \quad (3.3)$$

$$U_{rof}(t) = \sum_{k=1}^K x_k^{rof}(t) \frac{U_r \lambda_k}{U_r d_k + \lambda_k}, \quad (3.4)$$

in which  $x_i^{win}(t)$  denotes the state of the  $i$ -th alternative of the windows in year  $t$ , i.e., when  $x_i^{win}(t) = 1$ , it is chosen to retrofit the existing windows in year  $t$ , while if  $x_i^{win}(t) = 0$ , it is not chosen. The same kinds of variables, such as  $x_j^{wal}(t)$  and  $x_k^{rof}(t)$ , denote whether the  $j$ -th alternative of the insulation materials for the external walls and the  $k$ -th alternative of the insulation materials for the roof are chosen for retrofit in year  $t$ .

In a general building, the infiltration and ventilation heat gains of the cooling load is due to the air leakage into/out of the building. It contains two aspects: the sensible and latent heat gains.

The sensible heat gain in year  $t$ ,  $E_{sc}(t)$ , can be obtained by equation (3.5):

$$E_{sc}(t) = C_s Q_s C_{dd}(t), \quad (3.5)$$

where  $C_s$  is the sensible heat factor of air measured in  $\text{W}/(^{\circ}\text{C L/s})$  and  $Q_s$  is the air flow rate measured in  $\text{L/s}$ .



The latent heat gain in year  $t$ ,  $E_{lc}(t)$ , can be calculated by

$$E_{lc}(t) = C_l Q_s \Delta W(t) T_c(t), \quad (3.6)$$

where  $C_l$  is the latent heat factor of air measured in  $W/(L/s)$ ,  $\Delta W(t)$  is the difference of humidity ratio between the inside air and outdoor air in year  $t$  measured in  $kg/kg$ , and  $T_c(t)$  is the cooling time in year  $t$  measured in hours.

Solar heat gain is due to solar irradiation transferred through the windows. In a general building, the solar heat gain of the cooling load in year  $t$ ,  $E_{sl}(t)$ , can be obtained by equation (3.7):

$$E_{sl}(t) = A_{win} I_{win}(t) SHGC(t) T_s(t), \quad (3.7)$$

where  $I_{win}(t)$  is the solar irradiance on the windows of the building in year  $t$  measured in  $W/m^2$ ,  $SHGC(t)$  is the solar heat gain coefficient as a function of incident angle in year  $t$ , and  $T_s(t)$  is the solar radiation time in year  $t$ .

Internal heat gain is the heat generated by any source within an internal space, mainly occupancy, appliances and the lighting system. Thus, the internal heat gain of the cooling load of a building in year  $t$ ,  $E_i(t)$ , can be obtained by

$$E_i(t) = (\alpha_1 + \alpha_2 + \alpha_3) A_g T_{oc}(t), \quad (3.8)$$

where  $\alpha_1$ ,  $\alpha_2$ ,  $\alpha_3$  are the power load densities of people, lighting and appliances in the building measured in  $W/m^2$ , and  $T_{oc}(t)$  is the occupancy time during the cooling season in year  $t$  measured in hours.

Based on the detailed methods of calculating the energy consumption of the cooling load, which is supplied by the chiller in the HVAC system installed in the building, the electricity consumption of the cooling load can be calculated by equation (3.9):

$$E_{cool}(t) = \frac{E_{rc}(t) + E_{sc}(t) + E_{lc}(t) + E_{sl}(t) + E_i(t)}{SEER(t)}, \quad (3.9)$$

where  $SEER(t)$  represents the seasonal energy efficiency ratio (SEER) [131] in year  $t$ , measured in  $Btu/Wh$ . SEER is a ratio of the cooling output in BTU over the cooling season to the used watt-hours electricity input during the same period.

When the existing chiller in the HVAC system of the building is retrofitted with a new one, the SEER of the HVAC system will change. The value of the SEER in year  $t$  can be obtained by equation

(3.10):

$$SEER(t) = \sum_{c=1}^C x_c^{chi}(t) SEER_c, \quad (3.10)$$

where  $x_c^{chi}(t)$  denotes whether the  $c$ -th alternative of the chillers is chosen for retrofit in year  $t$ , i.e., when  $x_c^{chi}(t) = 1$ , it is chosen for retrofit, while it is not chosen when  $x_c^{chi}(t) = 0$ .  $SEER_c$  is the performance coefficient of the  $c$ -th alternative of the chillers.

### 3.2.2 Energy consumed by heating load

The heating load is the amount of heat energy that needs to be added to a space by the HVAC system to maintain the air temperature of the space at a designed level. The factors that may influence the heating load of a general building include transmission heat loss and infiltration and ventilation heat loss. To calculate the total energy consumption of the heating load, these two aspects must be modeled. Detailed information on modeling the energy consumption of the two aspects given below.

The transmission heat loss of a general building occurs through its envelope components, such as the windows, walls, roof, floor, etc. Therefore, the transmission heat gain of the heating load in year  $t$ ,  $E_{th}(t)$ , can be obtained by equation (3.11):

$$E_{th}(t) = H_{dd}(t)(A_{win}U_{win}(t) + A_{wal}U_{wal}(t) + A_{rof}U_{rof}(t) + A_{flr}U_{flr}(t)), \quad (3.11)$$

where  $H_{dd}(t)$  is the heating degree days in year  $t$  measured in °Ch.

The infiltration and ventilation heat loss of the heating load is due to the air leakage into and out of the building. It entails two aspects: the sensible and latent heat gains.

The sensible heat loss in year  $t$ ,  $E_{sh}(t)$ , can be determined by equation (3.12):

$$E_{sh}(t) = C_s Q_s H_{dd}(t). \quad (3.12)$$

The latent heat gain in year  $t$ ,  $E_{lh}(t)$ , can be determined by equation (3.13):

$$E_{lh}(t) = C_l Q_s \Delta W(t) T_h(t), \quad (3.13)$$

where  $T_h(t)$  is the heating time in year  $t$  measured in hours.

Based on the method of calculating the energy consumption of the heating load in detail, which is supplied by the heat pump in the HVAC system installed in the building, the electricity consumption of

the heating load can be calculated by equation (3.14):

$$E_{heat}(t) = \frac{E_{th}(t) + E_{sh}(t) + E_{lh}(t)}{HSPF(t)}, \quad (3.14)$$

where  $HSPF(t)$  is the heating seasonal performance factor (HSPF) [131] in year  $t$ , measured in Btu/Wh. HSPF is defined as the heating output in BTU during the heating season divided by the total electricity energy input in watt-hours during the same period.

When the existing heat pump in the HVAC system of the building is retrofitted with its alternatives, the HSPF of the HVAC system will change. The value of the HSPF in year  $t$  can be calculated by equation (3.15):

$$HSPF(t) = \sum_{h=1}^H x_h^{pum}(t) HSPF_h, \quad (3.15)$$

where  $x_h^{pum}(t)$  denotes whether the  $h$ -th alternative of the heat pumps is chosen for retrofit in year  $t$ , i.e., when  $x_h^{pum}(t) = 1$ , it is chosen for retrofit, while it is not chosen when  $x_h^{pum}(t) = 0$ .  $HSPF_h$  is the performance coefficient of the  $h$ -th alternative of the heat pumps.

### 3.2.3 Energy consumed by lights and appliances

In addition to the energy consumption resulting from the cooling and heating load, the lighting systems and appliances take large responsibility for the energy demand in a general building. This part of energy consumption in year  $t$ ,  $E_d(t)$ , can be obtained by equation (3.16):

$$E_d(t) = (P_l(t) + P_a)T_d(t), \quad (3.16)$$

where  $P_l(t)$  is the total power of the lighting systems of the building in year  $t$  measured in W,  $P_a$  is the total power of the appliances of the building in year  $t$  measured in W, and  $T_d(t)$  is the usage time of the lighting systems and appliances of the building in year  $t$  measured in hours.

### 3.2.4 Energy production of PV system

A PV system can convert solar irradiation into electrical energy directly. In addition, South Africa is one of the countries with the most abundant sunshine in the world. Therefore, a rooftop PV power supply system is considered to be installed in this study to reduce the energy demand of buildings. The energy contribution of the PV system to the building in year  $t$ ,  $E_{pv}(t)$ , can be determined

by [39, 41, 115, 116]

$$E_{pv}(t) = \sum_{p=1}^P (x_p^{pv}(t)\eta_p) \sum_{p=1}^P (x_p^{pv}(t)A_p^{pv})I_{pv}(t)\eta_s \sum_{t=1}^t N_{pv}(t), \quad (3.17)$$

where  $I_{pv}(t)$  is the solar irradiation on the PV system in year  $t$ th measured in  $\text{Wh/m}^2$ ,  $N_{pv}(t)$  is the number of the selected solar panels to be installed in year  $t$ ,  $x_p^{pv}(t)$  denotes whether the  $p$ -th alternative of the solar panels is chosen to be installed in the PV system during the retrofit in year  $t$ . For instance, when  $x_p^{pv}(t) = 1$ , it means that the  $p$ -th alternative is chosen to be installed in year  $t$ , while it is not chosen when  $x_p^{pv}(t) = 0$ .

### 3.2.5 Total energy consumption of a building

Based on the detailed modeling processes of the energy consumption of the cooling load, heating load, lighting systems and appliances and the energy generation of the PV system in the building in Sections 3.2.1- 3.2.4, the energy balance of the building in year  $t$ ,  $E_{tot}(t)$ , can be described by

$$E_{tot}(t) = E_{cool}(t) + E_{heat}(t) + E_d(t) - E_{pv}(t). \quad (3.18)$$

### 3.2.6 Energy intensity of a building

The EPC standard for buildings is the first national rating system on the energy efficiency of buildings developed by the government of South Africa. The purpose is to drive building owners or managers to improve the energy efficiency of buildings by implementing energy-efficient interventions to ensure compliance with the green building policy of the country.

According to the EPC rating system, there are seven levels for buildings concerning energy intensity, ranging from grade A for the most energy-efficient buildings to grade G for the most energy-inefficient buildings. The rating level of a building is determined by comparing the energy intensity of the building  $E_p(t)$  to a reference  $E_r$ . The energy intensity of a building can be described by

$$E_p(t) = \frac{E_{tot}(t)}{A_g}, \quad (3.19)$$

where  $A_g$  is the gross area of the building measured in  $\text{m}^2$ .

The value of the reference energy intensity,  $E_r$ , varies according to the occupancy types and climate zones of buildings [130]. The detailed requirements for obtaining a certain rating is provided in Table 3.1.

**Table 3.1.** Energy performance scale

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

### 3.3 OPTIMIZATION

The aim of the optimization model proposed in this chapter is to determine an optimal systematic retrofit plan for improving the energy efficiency of existing buildings to ensure compliance with the green building policy EPC in the most cost-effective way, i.e., maximizing the energy savings, minimizing the payback period of the building retrofit project and making sure of getting desired energy ratings from the EPC. The optimization model is helpful for decision makers to identify good investment projects. As mentioned in Section 3.1, the once-off long-term retrofit projects requiring substantial investments are broken down into multi-year smaller projects requiring relatively smaller investments. One should remember that the regulations on energy consumption of buildings may become more stringent in coming years and the target rating required to be achieved for each consecutive year will be different. Therefore, the optimization problem for building retrofit can be described in the following format:

$$\begin{aligned}
 & \mathbf{max} && \text{energy savings} \\
 & \mathbf{min} && \text{payback period} \\
 & \mathbf{s.t.} && \text{desired EPC rating, and budget available.}
 \end{aligned} \tag{3.20}$$

Details of the optimization problem are provided in the following subsections, with the assumptions given as follows:

- 1) The occupancy type of the building to be retrofitted during the whole project period remains unchanged. For instance, an office building will continue to be used as an office building and will not serve other purposes.
- 2) Proper maintenance for the items retrofitted during the project period will be implemented so that the energy savings of the retrofit project remain sustainable.
- 3) All of the existing items considered to be retrofitted in the building will only be retrofitted once over the whole project period. For example, if the chiller in the building's HVAC system is replaced with a certain counterpart, it will not be retrofitted again in the project period.

### 3.3.1 Decision variables

The building retrofit actions in this study can be divided into three parts, namely the retrofit of envelope components, including windows, walls and roof; the replacement of indoor facilities, including the lighting systems and the chiller and heat pump in the HVAC system; and the installation of a rooftop PV system. Assume that there are  $I$  alternatives of windows,  $J$  alternatives of wall insulation materials and  $K$  alternatives of roof insulation materials for the envelope retrofit,  $C$  alternatives of chillers and  $H$  alternatives of heat pumps for indoor facilities retrofit, and  $P$  alternatives of solar panels for the PV system installation. For the lighting systems, assume that there are  $m$  types of existing lights to be retrofitted and there are  $L_m$  alternatives for retrofitting the  $m$ -th type.

Let

$$\begin{aligned}
 X_{win} &= (x_1^{win}(1), \dots, x_I^{win}(1), \dots, x_1^{win}(T), \dots, x_I^{win}(T)), \\
 X_{wal} &= (x_1^{wal}(1), \dots, x_J^{wal}(1), \dots, x_1^{wal}(T), \dots, x_J^{wal}(T)), \\
 X_{rof} &= (x_1^{rof}(1), \dots, x_K^{rof}(1), \dots, x_1^{rof}(T), \dots, x_K^{rof}(T)), \\
 X_{chi} &= (x_1^{chi}(1), \dots, x_C^{chi}(1), \dots, x_1^{chi}(T), \dots, x_C^{chi}(T)), \\
 X_{pum} &= (x_1^{pum}(1), \dots, x_H^{pum}(1), \dots, x_1^{pum}(T), \dots, x_H^{pum}(T)), \\
 X_{pv} &= (x_1^{pv}(1), \dots, x_P^{pv}(1), \dots, x_1^{pv}(T), \dots, x_P^{pv}(T)), \\
 X_{lig_m} &= (x_1^{lig_m}(1), \dots, x_{L_m}^{lig_m}(1), \dots, x_1^{lig_m}(T), \dots, x_{L_m}^{lig_m}(T)),
 \end{aligned}$$

$$N = (N_{pv}(1), \dots, N_{pv}(T), N_{lig_1}(1), \dots, N_{lig_1}(T), \dots, N_{lig_m}(1), \dots, N_{lig_m}(T)).$$

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

$$X = [X_{win}, X_{wat}, X_{rof}, X_{chi}, X_{pum}, X_{pv}, X_{lig_1}, \dots, X_{lig_m}, N],$$

where  $N_{lig_m}(t)$  is the number of the  $m$ -th type of existing lighting technology retrofitted in year  $t$ ,  $x_{l_m}^{lig_m}(t)$  denotes whether the  $l_m$ -th alternative of the lighting for retrofitting the  $m$ -th type of existing lighting is chosen in year  $t$ . For instance,  $x_{l_m}^{lig_m}(t) = 1$  means it is chosen for retrofit while it is not when  $x_{l_m}^{lig_m}(t) = 0$ .

### 3.3.2 Objectives

The objectives of the optimization problem include maximizing the energy savings and minimizing the payback period of the building retrofit project. The models for calculating the energy savings and payback period are presented given below.

The energy saving resulting from the retrofit is the difference between the baseline energy consumption of the building and the energy consumed after the retrofit. The energy saving of the building retrofit project in year  $t$ ,  $ES(t)$  can be calculated by equation (3.21):

$$ES(t) = E_{tot}(t) - E_{base}, \quad (3.21)$$

where  $E_{base}$  is the baseline energy consumption of the building before the retrofit measured in Wh and  $ES(t)$  is the resultant energy savings in year  $t$  measured in Wh.

The payback period of the building retrofit project, taking into account the discounts of cash flow, can be calculated with equation (2.28).

In the calculation of cash flow, the tax incentive program is considered. The tax incentive program promotes the development of green buildings in South Africa by allowing building owners or managers to reduce the amount of their taxable income depending on the annual energy savings achieved in the buildings. Therefore, the actual monetary incentive for the owners or managers of buildings can be calculated by multiplying the offset amount by the tax rate of the individual/business, which is described by equation (3.22):

$$R(t) = (E_{tot}(t-1) - E_{tot}(t))\zeta_a\zeta_t, \quad (3.22)$$

where  $\zeta_a$  is the allowance rate set by the government measured in \$/Wh;  $\zeta_r$  is the tax rate for general businesses in South Africa.

Combining Eqs. (3.21) and (3.22), the discounted cash flows of the building retrofit project in year  $t$ ,  $C_f(t)$ , can be calculated by

$$C_f(t) = \frac{-C(t) + p(t)ES(t) + R(t)}{(1+d)^t}, \quad (3.23)$$

where  $C(t)$  is the retrofit cost in year  $t$  measured in \$, which can be calculated by

$$C(t) = A_{win} \sum_{i=1}^I x_i^{win}(t)C_i^{win} + A_{wal} \sum_{j=1}^J x_j^{wal}(t)C_j^{wal} + A_{rof} \sum_{k=1}^K x_k^{rof}(t)C_k^{rof} + \sum_{c=1}^C x_c^{chi}(t)C_c^{chi} \\ + \sum_{h=1}^H x_h^{pum}(t)C_h^{pum} + N_{pv}(t) \sum_{p=1}^P x_p^{pv}(t)C_p^{pv} + \sum_{m=1}^m \sum_{l_m=1}^{L_m} x_{l_m}^{lig_m}(t)C_{l_m}^{lig_m} N_{lig_m}(t), \quad (3.24)$$

where  $C_c^{chi}$  and  $C_h^{pum}$  are the cost of the  $c$ -th alternative of the chillers and  $h$ -th alternative of the heat pumps, respectively, measured in \$,  $C_{l_m}^{lig_m}$  is the unit cost of the  $l_m$ -th alternative of the lighting used to retrofit the  $m$ -th type of existing lighting technologies measured in \$.

With the weighted sum method [108, 109, 110], the multi-objective problem in this study can be formulated into a single-objective optimization problem as equation (3.25):

$$J = -w_1 \sum_{t=1}^T ES(t) + w_2 T_p, \quad (3.25)$$

where  $w_1$  and  $w_2$  are positive weights. During the optimization process, the values of the two objectives are normalized with respect to their base case for the convenience of tuning the weighting factors.

### 3.3.3 Constraints

The constraints of the optimization problem include three parts, including budget limit, EPC limit and physical limit.

Firstly, the budgets allocated to each year for the building retrofit project are limited, which can be described by

$$C(t) \leq \beta_t, \quad (3.26)$$

where  $\beta_t$  is the budget allocated to the building retrofit project in year  $t$  measured in \$.

Secondly, to make sure the energy performance of the building after retrofit can reach a desired EPC rating in year  $t$ , the building must meet the corresponding requirement of the rating level from the EPC



standard, which can be described by

$$E_p(t) < \delta(t)E_r, \quad (3.27)$$

where  $\delta(t)$  is a coefficient, which takes the values from Table 3.1. For instance,  $\delta(t) = 1.1$  ensures that the energy performance of the building must achieve a rating with D at least in year  $t$ .

The physical limit of the building retrofit project consists of two parts, including the limited installation area for the PV system on the roof of the building and the decision variables' boundary limits.

The area limit is described by

$$\sum_{t=1}^T \sum_{p=1}^P x_p^{pv}(t) A_p^{pv} N_{pv}(t) \leq A_{eff}. \quad (3.28)$$

The boundary limits on the decision variables are described by

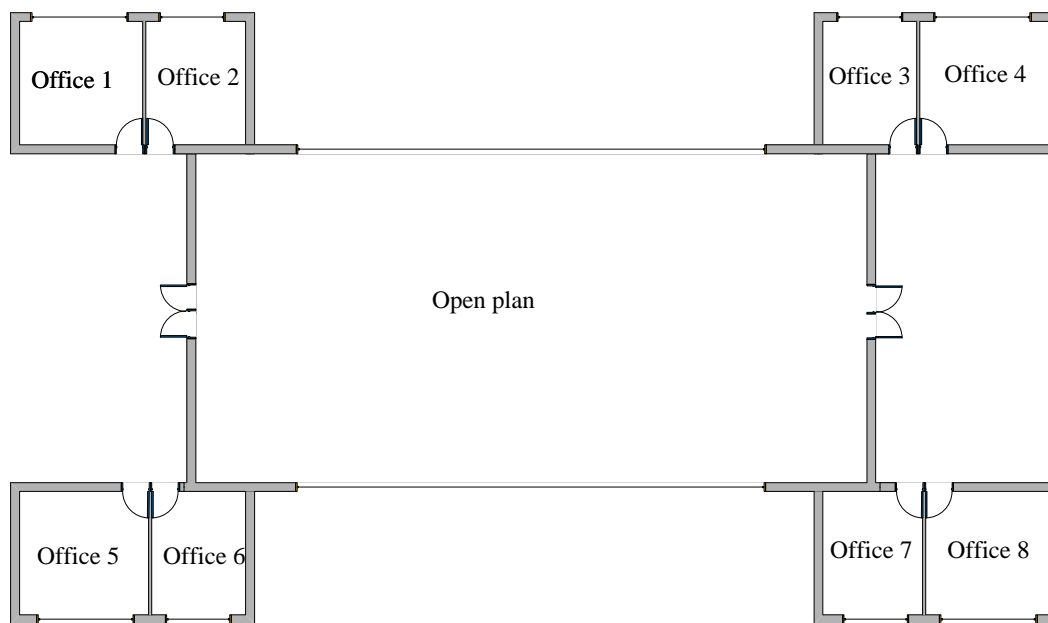
$$\left\{ \begin{array}{l} \sum_{i=1}^I x_i^{win}(t) \in \{0, 1\}, \text{ for } x_i^{win}(t) \in \{0, 1\}, \forall i \in \{1, 2, \dots, I\} \\ \sum_{j=1}^J x_j^{wal}(t) \in \{0, 1\}, \text{ for } x_j^{wal}(t) \in \{0, 1\}, \forall j \in \{1, 2, \dots, J\} \\ \sum_{k=1}^K x_k^{rof}(t) \in \{0, 1\}, \text{ for } x_k^{rof}(t) \in \{0, 1\}, \forall k \in \{1, 2, \dots, K\} \\ \sum_{c=1}^C x_c^{chi}(t) \in \{0, 1\}, \text{ for } x_c^{chi}(t) \in \{0, 1\}, \forall c \in \{1, 2, \dots, C\} \\ \sum_{h=1}^H x_h^{pum}(t) \in \{0, 1\}, \text{ for } x_h^{pum}(t) \in \{0, 1\}, \forall h \in \{1, 2, \dots, H\} \\ \sum_{p=1}^P x_p^{pv}(t) \in \{0, 1\}, \text{ for } x_p^{pv}(t) \in \{0, 1\}, \forall p \in \{1, 2, \dots, P\} \\ \sum_{l_m=1}^{L_m} x_{l_m}^{lign}(t) \in \{0, 1\}, \text{ for } x_{l_m}^{lign}(t) \in \{0, 1\}, \forall l_m \in \{1, 2, \dots, L_m\} \\ \sum_{t=1}^T N_{lign}(t) \leq N_{l_m}, \forall t \in \{1, 2, \dots, T\} \end{array} \right. , \quad (3.29)$$

where  $N_{l_m}$  is the maximum number of the  $m$ -th type of existing lamps available for retrofit.

### 3.4 CASE STUDY

#### 3.4.1 Case information

To analyze the effectiveness and feasibility of the optimization model, an existing office building situated in Pretoria, South Africa is used as a case study. The building has a gross area of 568 m<sup>2</sup> and consists of two floors with the same structure, which is shown in Fig. 3.1.



**Figure 3.1.** Floor plan of the office building under study

The retrofit plan for this building includes a set of actions. For the envelope, it is considered to replace the windows with better alternatives and to install insulation materials on the walls and roof. In view of the indoor appliances, the existing lighting system is to be upgraded by more energy-efficient models and the chiller and heat pump in the HVAC system are to be retrofitted with more energy-efficient ones. Installation of a PV power supply system is also part of the retrofit actions. Detailed information on the systems/components used for the retrofit, including windows, wall and roof insulation materials, chiller, heat pump, lighting and PV panels, is given in Tables 2.2-2.4 and 3.2-3.5. In Table 3.5, three alternative lighting technologies are listed for the retrofit of each existing technology. The baseline energy consumption of the building before the retrofit is 120.6 MWh per year. The discount rate involved in the optimization process is set at 6% according to South African statistics <sup>2</sup>. The rate of increase in the electricity price in South Africa is determined as 12.69% according to the average increase rate of electricity published by Eskom <sup>3</sup>.

The EPC rating system gives this particular building studied an E rating before the retrofit. Therefore, to improve the energy efficiency of the building in order to obtain a D rating for policy compliance and subsequently C, B and A ratings in the following years, the retrofit plan considers an implementation

<sup>2</sup><http://www.statssa.gov.za/>

<sup>3</sup>Eskom. Historical average price increase. [http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Pages/Tariff\\_History.aspx](http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Pages/Tariff_History.aspx). Accessed 7th Dec. 2016.

**Table 3.2.** Information on window alternatives

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

**Table 3.3.** Information on chiller alternatives

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

**Table 3.4.** Information on heat pump alternatives

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

period for the retrofit of four years. In particular, the retrofit plan will improve the EPC rating of this building to D in year one and to grade C in year two, and eventually to grade A in year four to first ensure policy compliance and then pursue better energy efficiency.

The optimization problem is solved by a genetic algorithm. During the optimization process, the budgets allocated to each year for the retrofit are set at \$2000, \$7000, \$30000 and \$70000, respectively. The optimal results obtained with different weighting factors are shown in the following subsections. In addition, the impact of the tax incentive program on the retrofit project is investigated.

**Table 3.5.** Information on lighting technology alternatives

$l_m$	Existing lighting	$N_{l_m}$	Alternatives	$C_{l_m}^{ligm}$ (\$)
$l_1$	2-lamp 4' T8 fixture 70 W	80	2-lamp 4' T5 14 W	19.0
			2-lamp 4' T5 18 W	20.5
			2-lamp 4' T5 36 W	10.0
$l_2$	PAR 38 - 65 W	48	CFL lamp 7 W	35.4
			CFL lamp 14 W	37.1
			CFL lamp 20 W	27.6
$l_3$	Halogen 50 W - 12 V	56	LED flood 7 W	8.5
			LED flood 10 W	12.2
			LED flood 14 W	17.7
$l_4$	Incandescent 100 W	32	LED bulb 12 W	79.5
			LED bulb 17 W	53.0
			LED bulb 20 W	42.4
$l_5$	Incandescent 60 W	68	LED bulb 12 W	79.5
			LED bulb 17 W	53.0
			LED bulb 20 W	42.4

### 3.4.2 Results with $w_1=0.7$ , $w_2=0.3$

To strike a balance between the energy savings and economic benefits of the building retrofit project, the optimization problem is solved first with the weighting factors of the objective function set to  $w_1 = 0.7$  and  $w_2 = 0.3$ . The corresponding optimal results achieved by the built model, taking into account the tax incentive policy, are presented in Table 3.6.

The table gives detailed retrofit actions for the building during the four years. In Table 3.6, the items

**Table 3.6.** The optimal solution with weighting factors  $w_1 = 0.7, w_2 = 0.3$ 

	Year 1	Year 2	Year 3	Year 4
$\beta(t)$ (\$)	2000	7000	30000	70000
$C(t)$ (\$)	1425	6991	18959	69742
Window's option	0	0	0	0
Wall's option	0	10	0	0
Roof's option	0	0	0	2
Chiller's option	0	0	1	0
Heat pump's option	0	0	1	0
PV's option	0	0	0	5
$N_{pv}$	0	0	0	97
$L_1$	1	3	0	0
$N_{lig1}$	75	5	0	0
$L_2$	0	2	0	0
$N_{lig2}$	0	48	0	0
$L_3$	0	3	0	0
$N_{lig3}$	0	56	0	0
$L_4$	0	2	0	0
$N_{lig4}$	0	32	0	0
$L_5$	0	2	3	0
$N_{lig5}$	0	10	58	0
$T_p$ (month)	8	20	44	90
$ES(t)$ (kWh)	12096	34433	58111	93852
$ES_p(t)$	10%	29%	48%	78%
$E_p(t)$	1.01	0.80	0.58	0.25

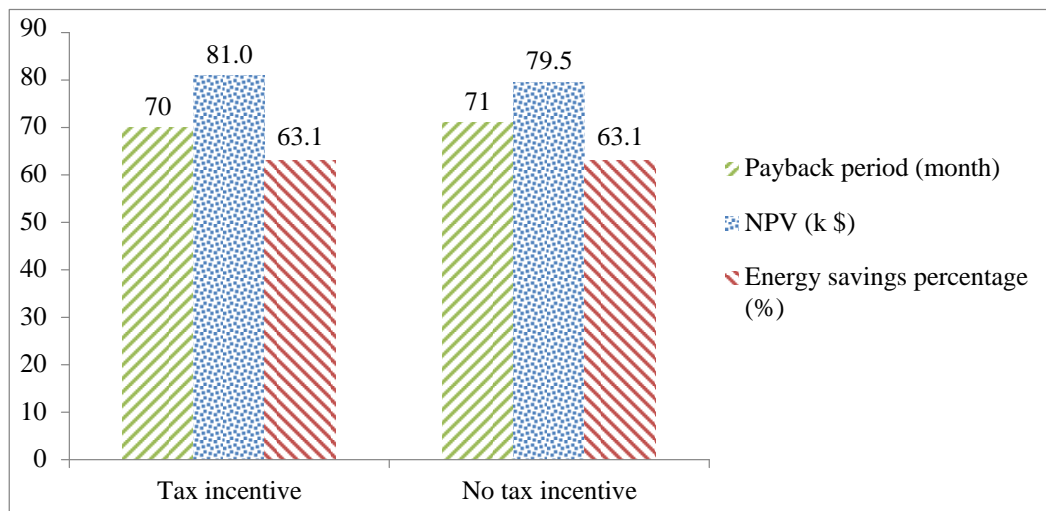
in the first column from the second to the ninth row represent the retrofit options for the windows, walls, roof, chiller, heat pump and PV system, respectively.  $L_1, L_2, L_3, L_4$  and  $L_5$  represent the retrofit options for the five existing lighting technologies, respectively.  $N_{pv}, N_{lig1}, N_{lig2}, N_{lig3}, N_{lig4}$  and  $N_{lig5}$ , represent the numbers of installed solar panels and replaced lights of the five types of existing lighting technologies, respectively. That is to say, the optimal retrofit plan for the building is indicated by the numbers in the last four columns from the fourth to the twentieth row of the table. For instance, the

number '2' in the sixth row of the last column indicates that the second alternative of the roof insulation materials listed in Table 2.3 will be installed in the fourth year. The combination of the numbers in the third column, '2' for  $L_2$  and '48' for  $N_{lig_2}$ , represents that 48 of the second type of the existing lights are to be retrofitted with the second alternative listed in Table 3.5 in the second year. A number '0' in the table means that the corresponding item will not be retrofitted in that year.

The items  $ES(t)$  and  $ES_p(t)$  in Table 3.6 represent the energy savings and the percentage of energy savings compared to the baseline energy consumption. It can be seen that the energy savings of the retrofit project keeps increasing year by year, which is because some items in the building are retrofitted every year. The table also shows the payback periods of the investments allocated to each year. The payback periods of the investments are not long, which is attractive to decision makers. For instance, the retrofit project takes eight months to recover the \$1452 investment in the first year. Comparing the payback periods and the retrofit actions of the four years, one can see that retrofitting the lighting systems is the most cost-effective option, which is followed by retrofitting the components in the HVAC system. The time it takes to recover the investment of retrofitting the envelope components of the building and installing a PV power supply system is longest, although these elements can yield great energy savings.

Therefore, the optimal building retrofit plan is actually a best combination of retrofit actions instead of simply retrofitting the most energy-efficient or the cheapest facilities. In addition to maximizing energy savings and minimizing the payback period, another purpose of the retrofit plan is to ensure the building under study achieves a D rating from the EPC standard in the first year and then achieves better ratings in the following years. The results in Table 3.6 indicate that only the first type of the existing lighting technologies is retrofitted in the first year and this helps the building to achieve a D energy rating. To achieve a C rating in the second year, most of the lighting technologies are retrofitted and the tenth alternative of the insulation materials listed in Table 2.2 are installed in the walls. The reason why not all the lighting technologies are replaced in the second year is that more energy savings are needed to reach the C level from EPC and the wall retrofit can satisfy the requirement. The remaining existing lighting technologies and the facilities in the HVAC system are retrofitted in the third year to ensure the energy performance of the building can obtain a B rating. Moreover, the second alternative of the roof insulation materials and 97 of the fifth alternative of the solar panels listed in Table 2.4 are installed in the fourth year, resulting in an A rating.

The accumulative energy savings, NPV of the building retrofit project in a ten-year evaluation period and the payback period of the total investment are presented in Fig. 3.2. It can be seen that the office building under study can achieve 761.6 MWh of energy savings and \$81003 of cost savings with a payback period of 70 months by applying the optimal retrofit plan, considering the tax incentive program. As some of the buildings owned by the government in South Africa do not qualify for



**Figure 3.2.** Impact of tax incentive on the retrofit project with  $w_1 = 0.7$ ,  $w_2 = 0.3$

the tax incentive, the optimization problem is solved again without taking the tax incentive program into consideration, using the same weighting factors for investigating the impact of the tax incentive program on the building retrofit project conveniently. The resulting energy and economic benefits are shown in Fig. 3.2. Compared with the results of taking the tax incentive policy into account, one finds that the payback period is longer and the cumulative NPV is less in this case. Nevertheless, the influence of the tax incentive policy on the building retrofit project is limited. For instance, the payback period of the total investment increases by 1.4%, which is about one month, and the NPV decreases by 1.9%, which is about \$1500.

### 3.4.3 Results with $w_1=0$ , $w_2=1$

To study how to obtain a shorter payback period instead of more energy savings through the building retrofit project by tuning the weighting factors in the objective function, the optimization problem is solved with  $w_1 = 0$  and  $w_2 = 1$ . The corresponding optimal results taking into account the tax incentive policy are presented in Table 3.7.

**Table 3.7.** The optimal solution with weighting factors  $w_1 = 0, w_2 = 1$ 

	Year 1	Year 2	Year 3	Year 4
$\beta(t)$ \$	2000	7000	30000	70000
$C(t)$ \$	475	6997	12158	64139
Window's option	0	0	0	0
Wall's option	0	0	0	0
Roof's option	0	0	0	0
Chiller's option	0	3	0	0
Heat pump's option	0	0	0	0
PV's option	0	0	5	5
$N_{pv}$	0	0	4	91
$L_1$	0	3	1	0
$N_{lig1}$	0	56	24	0
$L_2$	0	0	2	0
$N_{lig2}$	0	0	48	0
$L_3$	1	0	0	0
$N_{lig3}$	56	0	0	0
$L_4$	0	0	2	0
$N_{lig4}$	0	0	32	0
$L_5$	0	0	1	0
$N_{lig5}$	0	0	68	0
$T_p$ (month)	5	22	24	88
$ES(t)$ (kWh)	6935	26655	56099	89604
$ES_p$	6%	22%	47%	74%
$E_p(t)$	1.05	0.87	0.60	0.29

With the weighting factors  $w_1 = 0$  and  $w_2 = 1$ , the retrofit costs of each year are \$475, \$6997, \$12158 and \$64139, respectively. The table shows that the energy saving of the building retrofit project keeps increasing from 6.9 MWh (6% compared to the baseline energy consumption) in the first year to 89.6 MWh (74% compared to the baseline energy consumption) in the fourth year. The payback period of the investment allocated to each year keeps increasing from five months in the first year to 88 months in the fourth year. This phenomenon can be explained by the short payback period of retrofitting the



lighting systems and HVAC system and the long payback period of retrofitting the envelope system and installing the PV system.

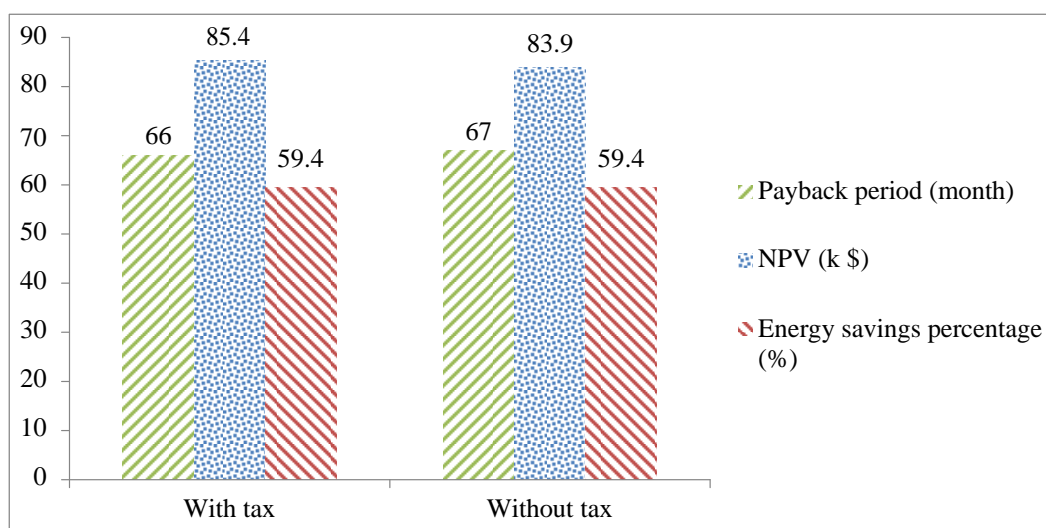
Comparing the values of  $E_p(t)$  in Table 3.7 with the requirements in Table 3.1, one finds that the energy efficiency of the building has been improved to grade D, C, B and A from EPC in proper order in the four years by applying the optimal retrofit plan. It can be seen from the table that 56 of the third type of existing lights are replaced with the first alternative in the first year to meet the basic requirement of grade D. In the second year, the chiller in the HVAC system and 56 of the first type of the existing lights are replaced with the third alternatives, respectively, resulting in a C rating. Most of the remaining existing lights are replaced and a rooftop PV system is installed with four of the fifth alternative of the solar panels listed in Table 2.4 in the third year. To make sure the energy intensity of the building meets the requirement of grade A in the fourth year, 91 more solar panels are built into the PV system. The envelope components of the building are not retrofitted during the whole retrofit period. This is because the optimal retrofit plan in this case favors a shorter payback period instead of more energy savings, while the payback period of the envelope retrofit is very long.

The total energy savings and economic benefits of the building retrofit project during the project period are presented in Fig. 3.3. It can be seen that the optimal retrofit plan can help the office building under study to obtain 716.9 MWh of energy savings and \$85385 of cost savings with a payback period of 66 months.

With the weighting factors  $w_1 = 0$  and  $w_2 = 1$ , the optimization problem is solved again without considering the tax incentive program. The resulting energy and economic benefits are shown in Fig. 3.3. It can be seen that the payback period is longer and the cumulative NPV is less compared with the results that take the tax incentive policy into consideration. To be specific, the payback period of the building retrofit project increases by 1.0%, which is about one month, and the NPV decreases by 1.7%, which is about \$1500.

#### 3.4.4 Results with $w_1=1$ , $w_2=0$

To study how to obtain more energy savings instead of a shorter payback period of the building retrofit project by tuning the weighting factors in the objective function, the optimization problem is solved



**Figure 3.3.** Impact of tax incentive on the retrofit project with  $w_1 = 0$ ,  $w_2 = 1$

with  $w_1 = 1$  and  $w_2 = 0$ . The corresponding optimal results, taking into account the tax incentive policy, are presented in Table 3.8.

The table shows that the retrofit costs of each year are \$1999, \$6970, \$29901 and \$69626, respectively. The budgets allocated to the four years are almost exhausted. The energy savings of the building retrofit project keep increasing from 14.6 MWh (12% compared to the baseline energy consumption) in the first year to 100.4 MWh (83% increase compared to the baseline energy consumption) in the fourth year. This is because more facilities of the building are retrofitted in the following years. The payback period of the individual investment assigned to each year keeps increasing from 10 months in the first year to 87 months in the fourth year.

The values of  $E_p(t)$  in Table 3.8 are 0.98, 0.80, 0.53 and 0.19 in the four years, respectively. Referring to the requirements of different ratings in Table 3.1, it can be seen that the energy efficiency of the building has been improved by applying the retrofit plan, resulting in the building achieving the EPC energy ratings D, C, B and A consecutively in the four years. Table 3.8 shows that the lights are almost all retrofitted in the first two years, which helps the building reach the requirements of grades D and C. To get a B rating in the third year, a set of retrofit actions take place, including replacing the remaining existing lights, replacing the chiller in the HVAC system with the second alternative listed in Table 3.3, retrofitting the walls with its second alternative of the wall insulation materials listed in Table 2.2 and installing a PV system with the fourth alternative of the solar panels listed in Table 2.4. The scale of

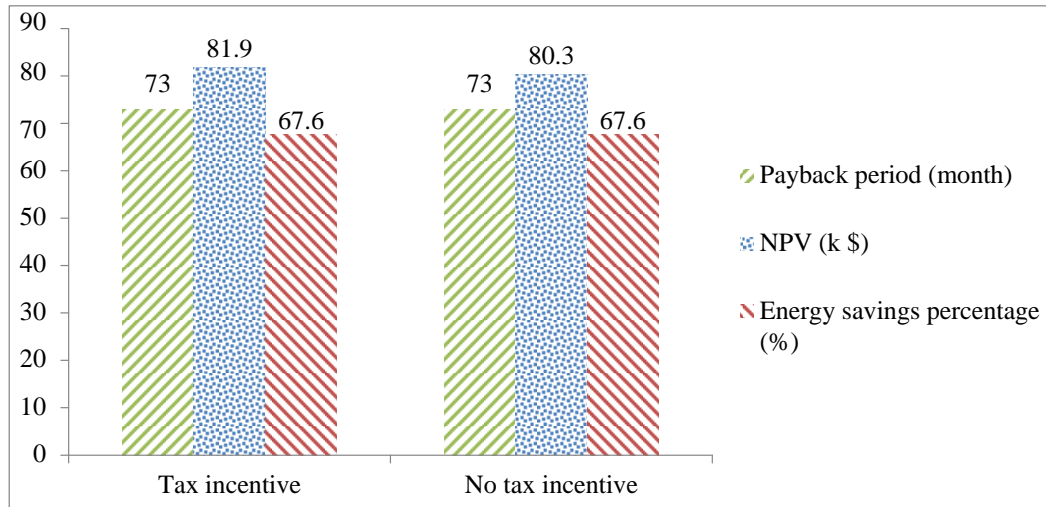
**Table 3.8.** The optimal solution with weighting factors  $w_1 = 1, w_2 = 0$ 

	Year 1	Year 2	Year 3	Year 4
$\beta(t)$ \$	2000	7000	30000	70000
$C(t)$ \$	1999	6970	29901	69626
Window's option	0	0	0	0
Wall's option	0	0	0	0
Roof's option	0	0	2	0
Chiller's option	0	0	2	0
Heat pump's option	0	0	0	0
PV's option	0	0	4	4
$N_{pv}$	0	0	23	80
$L_1$	3	0	0	0
$N_{lig1}$	80	0	0	0
$L_2$	3	2	2	0
$N_{lig2}$	5	40	3	0
$L_3$	3	0	2	0
$N_{lig3}$	55	0	1	0
$L_4$	3	3	0	0
$N_{lig4}$	2	30	0	0
$L_5$	0	1	2	0
$N_{lig5}$	0	53	15	0
$T_p$ (month)	10	22	56	87
$ES(t)$ (kWh)	14645	34759	63509	100377
$ES_p$	12%	29%	53%	83%
$E_p(t)$	0.98	0.80	0.53	0.19

the PV system is expanded by installing 80 more solar panels in the fourth year, resulting in an A rating.

The accumulative energy savings and economic benefits of the building retrofit project during the project period are presented in Fig. 3.4. It can be seen that the office building under study can achieve 815.6 MWh of energy savings and \$81863 of cost savings with a payback period of 73 months by

applying the optimal retrofit plan.



**Figure 3.4.** Impact of tax incentive on the retrofit project with  $w_1 = 1$ ,  $w_2 = 0$

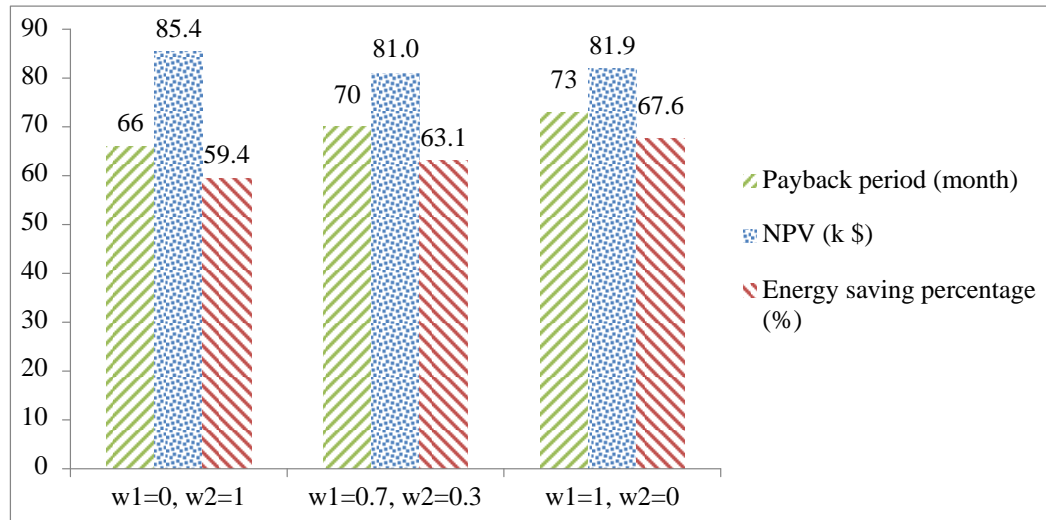
With the same weighting factors, the optimization problem is solved again without considering the tax incentive program. The resulting energy and economic benefits are shown in Fig. 3.4. It can be seen that the NPV is less (about 2.0% decrease) compared with that considering the tax incentive. However, the payback periods of the two situations are almost the same. This illustrates that the tax incentive has little impact on the building retrofit project.

### 3.4.5 Results comparison with different weighting factors

In the above subsections, the optimization problem is investigated with different weighting factors in the situations of considering and not considering the tax incentive program. In particular, the impact of the tax incentive on the retrofit project is analyzed. In this part, the impact of the weighting factors on the retrofit project will be described intuitively based on the results shown in Fig. 3.2-3.4.

Firstly, the tax incentive program is not taken into consideration. The resulting energy savings and economic benefits of the three optimal retrofit plans obtained with different weighting factors are shown in Fig. 3.5. It can be seen that the energy savings increase and the payback period decreases when the values of their corresponding weighting factors grow. To be exact, the percentage of the energy savings compared with the baseline energy consumption of the building increases from 59.4%

to 67.6% with its weighting factor,  $w_1$ , growing from zero to one. The payback period of the retrofit project decreases from 73 to 66 months with its weighting factor,  $w_2$ , growing from zero to one. The NPV fluctuates.

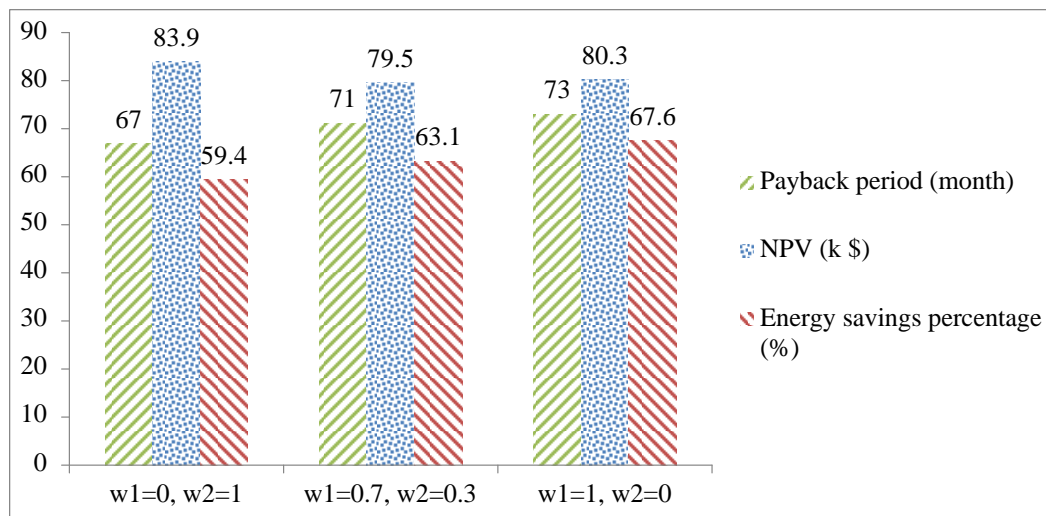


**Figure 3.5.** Optimal results with different weighting factors considering tax incentive

This is then the situation, not taking into account the tax incentive program. The optimal results with different weighting factors are shown in Fig. 3.6. It can be seen that the energy savings and the payback period change in the same way as those in Fig. 3.5 when their corresponding weighting factors  $w_1$  and  $w_2$  grow. For instance, the payback period in Fig. 3.6 decreases from 73 to 67 months when  $w_2$  grows from zero to one.

Combining the results in Fig. 3.5 and Fig. 3.6, one finds that decision makers can get maximum energy savings by setting  $w_1 = 1$  and  $w_2 = 0$  and a minimum payback period by setting  $w_1 = 0$  and  $w_2 = 1$ , i.e., the proposed optimization model encourages decision makers to participate in the optimization process. Decision makers can achieve a desired optimal retrofit plan according to their expectations for energy and economic benefits by tuning the weighting factors.

In addition, the payback periods of retrofitting the building components with different options are different. With the help of the optimization model, decision makers can avoid simply choosing options that are the cheapest or the most energy-efficient intuitively. This case study demonstrates the feasibility and effectiveness of the proposed optimization model for building retrofit projects.



**Figure 3.6.** Optimal results with different weighting factors, not considering tax incentive

### 3.5 CONCLUSION

In this chapter, an optimization model for building retrofit planning considering both the envelope components and indoor appliances is presented. The purpose of this optimization model is to improve the energy efficiency of existing buildings by implementing energy-efficient interventions to achieve a desired energy rating from the energy performance certificate for buildings (EPC) in the most profitable way, aiming at complying with the green building policy in South Africa.

The retrofit actions considered for existing buildings in this chapter entail upgrading the envelope system, lighting system and HVAC system to improve the energy efficiency of the buildings and installing a rooftop PV power supply system to reduce the energy demand of the buildings from the grid. In this study, the proposed model breaks up the once-off long-term building retrofit project requiring substantial investment into multiple smaller projects requiring relatively smaller investments with short payback periods, which is helpful to mitigate the concerns of decision makers and attract more investments for similar building retrofit projects. In addition, the tax incentive policy of the country is taken into account during the optimization process to shorten the payback period of the building retrofit project further. The optimization problem is solved with the weighted sum method, which provides a convenient method for decision makers to obtain a desired optimal retrofit plan by tuning the weighting factors according to their preferences for energy savings and the payback period, which are important indicators of investments. The results of a case study demonstrate the effectiveness

and feasibility of the proposed model for building retrofit planning. In addition, the results indicate that the impact of the tax incentive program on building retrofit projects is not obvious.

# **CHAPTER 4 BUILDING RETROFIT OPTIMIZATION MODELS USING NOTCH TEST DATA**

## **4.1 INTRODUCTION**

There are two main motivations for the simplified models developed in this chapter. Firstly, the optimization model proposed in Chapter 3 is difficult to solve. The large numbers of items to be retrofitted and their retrofit options in a general retrofit problem result in a high-dimension optimization problem. Coupled with the mixed integer decision variables involved, the formulated problem is a high dimensional ‘NP-hard’ problem. Moreover, the intrinsic multi-objective and nonlinear characteristics of the optimization problem make it even more challenging to obtain the optimal solution. This situation is further worsened especially when the building to be retrofitted has a large number of floors (or similar functional areas) that cause a linear increase in the dimension of the decision variables. A similar problem is experienced by managers looking at retrofit options for a building portfolio consisting of multiple buildings. Given the large number of items in a building for possible retrofit, it is very difficult to evaluate all the possibilities of retrofitting each energy consuming item, since the problem is NP-hard and the available algorithms to search for the optimal solution can easily be trapped in local extrema without being able to get close to the global solution. A method that helps to reduce the complexity of solving the problem formulated in Chapter 3 is therefore needed. Secondly, there is a large number of parameters, such as energy saving of each item, cost of these and what are the existing technologies available in the building, etc., that need to be obtained for the model given in Chapter 3. This requires a detailed energy audit of the buildings to be retrofitted, which is an expensive bottom-up modeling exercise.



Therefore, this chapter puts forward two methods to reduce the difficulty of solving the optimization problem and help to reduce the cost of the energy audit process. These simplified methods are based on the concept of grouping and measured energy savings data from sample retrofits. The grouping method is used to categorize items to be retrofitted into several homogeneous groups. Items are considered to be homogeneous and are assigned to a group if they have the same energy performance, inherent properties, working environment and operating schedules. This is motivated by the fact that energy consuming systems in a building can be classified into lighting systems, HVAC systems, envelope systems, etc., and each of these systems usually consists of items with same characteristics. On a larger scale, each of these systems in a big building or building group can be treated as an virtual 'item' because of their same functionality and characteristics.

Making use of the grouping method, the dimension of the decision variables can be reduced significantly because the solution will only look at whether a group of items should be retrofitted or not instead of doing the same for each single item. This is also in good agreement with the expectations of the decision makers because they will usually retrofit the whole group of the same units (for example, replacing all light bulbs in a lighting system) because of labor cost and easy maintenance considerations. In addition, the grouping method also reduces the level of detail of the energy audit required. Instead of conducting a comprehensive bottom-up audit, one can conduct a simplified audit by design and gathering data for each group of items, which will reduce the cost of energy audit favorably. Therefore, the method of grouping is helpful to reduce the difficulty of solving the building retrofit problem with a large number of possible retrofit items involved [132].

In this study, items with the same energy performance and cost implications are grouped together and the resulting group is treated as a homogeneous group. In addition, it must be pointed out that this study considers buildings with a large number of similarly designed and operated floors or functional areas. All homogeneous items within the boundary of a floor or a functional area comprise a subset of the overall homogeneous group of items for the whole building and will be termed an 'item' of the overall group in the rest of this chapter. The optimization will determine how many of these subsets or virtual 'items' should be retrofitted in the planning phase. This is done for the purpose of obtaining more retrofit solutions with different savings and cost implications. If, on the other hand, all same items in the whole building are treated as a group and the optimization only determines whether that group of items will be retrofitted or not, the decision maker will have very limited retrofit solutions and those solutions are usually not optimal in the sense that they do not consider the detailed information of

the building. In other words, the proposed grouping helps to strike a balance between the difficulty of solving the retrofit optimization problem and the level of details considered by the optimization.

After dividing the retrofitted items of the building into several homogeneous groups, the overall retrofit performance of the building, such as energy savings and cost, can be evaluated by investigating the performance of retrofitting an individual member and the number of members of each homogeneous group.

The building retrofit problem is further simplified by making use of available measured energy savings from retrofitting items of a homogeneous group, taking advantage of the aforementioned grouping method. This is supported by the large number of energy conservation initiatives implemented across the world. In South Africa, for example, many building retrofit projects have been implemented and the energy savings of these projects have been quantified with the measurement and verification (M&V) approach [46]. The verified energy savings of retrofitting different systems in a general building, including the envelope system, lighting system, HVAC system, etc., are the so-called 'notch test' data, which can be used to simplify the optimization problem. To be specific, knowing the potential energy savings and corresponding cost of retrofitting each subsystem of one floor of a building with a certain alternative, one can determine the best combination of subsystems and alternatives that could be used for the whole-building retrofit so that the given objectives of the optimization problem are achieved. Consequently, the dimension of the optimization problem in Chapter 3 can be decreased significantly from many variables, concerning whether each single item of the building should be retrofitted or not, if it should be retrofitted, which alternative should be chosen and how many of this type of items should be retrofitted, to one variable representing whether a certain subsystem for each floor of the building should be retrofitted or not. And the need of a detailed energy audit is eliminated.

Based on the grouping and notch test data, two methods are put forth in this chapter to simplify the optimization problem, as detailed in the following sections. In the rest of this chapter, all modeling formulations are for buildings with several floors. It is noted that the same formulation can be applied to buildings with several functional areas or a group of buildings with the similar functionalities.

In summary, this chapter presents two simplified optimization models to reduce the complexity of the systematic whole-building retrofit planning problem, considering both the envelope system and indoor facilities of a building, taking into account the EPC standard. Detailed formulations of the two

simplified optimization models are presented in Sections 4.2-4.4. After that, a case study and its results are analyzed in Section 4.5. Finally, conclusions are drawn in Section 4.6.

## 4.2 PROBLEM DESCRIPTION

The aims of the two models are the same as those of the optimization model presented in Chapter 3, namely, to maximize energy savings, minimize the payback period of building retrofit projects and ensure that the buildings can obtain a good energy rating from the EPC standard. Therefore, the optimization building retrofit problem to be solved with the two simplified methods can be described in the same format as follows:

$$\begin{aligned} & \mathbf{max} && \text{energy savings} \\ & \mathbf{min} && \text{payback period} \\ & \mathbf{s.t.} && \text{budget available and EPC requirement.} \end{aligned} \tag{4.1}$$

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

- 1) The building to be retrofitted has the same structure for each floor.
- 2) Each floor of the building is considered for retrofitting energy consumption subsystems, such as lighting, the envelope, etc., instead of single items. For instance, all the luminaries rather than only some of them on one floor will be replaced with new ones if that floor is designated for retrofitting the lighting system.
- 3) Proper maintenance for the items retrofitted during the project period is implemented so that the energy savings of the retrofit project are sustainable.

In this chapter, the energy users in a building are grouped into the lighting system, envelope system (windows and wall), HVAC system (chiller and heat pump) and roof system for retrofit. In addition, a PV power supply system is considered to be installed for the same purpose as stated in Chapter 2 and 3.

Because the structure of each floor of the building is the same, the energy performance, inherent properties, working environment and operating schedules of the lighting subsystem and envelope

subsystem of each floor are considered to be the same. According to grouping, all the lights in the building can be grouped into a homogeneous group with all the lights installed on each floor as a virtual item of this group. The same is done for the envelope and HVAC systems. The roof only has one item because for each building, there is only one roof structure. With this grouping and notch test data for retrofitting an item in these homogeneous groups, one can determine the impact of retrofitting a homogeneous group of items (subsystems) on the whole building.

Assume that there are  $I$  alternatives of windows,  $J$  alternatives of wall insulation materials and  $K$  alternatives of roof insulation materials for retrofitting the envelope system,  $C$  alternatives of chillers and  $H$  alternatives of heat pumps for retrofitting the HVAC system, and  $P$  alternatives of solar panels for the PV system installation. For the lighting systems, assume that there are  $m$  types of existing lights to be retrofitted and there are  $L_m$  alternatives for retrofitting the  $m$ -th type. It follows that there are  $(I + 1)(J + 1)$  retrofit options for the envelope system,  $(C + 1)(H + 1)$  retrofit options for HVAC systems and  $(L_1 + 1)(L_2 + 1) \dots (L_m + 1)$  retrofit options for lighting systems and  $(K + 1)$  retrofit options for the roof, as well as  $(P + 1)$  options for PV system installation for the building. Let  $e$ ,  $v$  and  $u$  denote that the  $e$ -th option for the envelope system, the  $v$ -th option for the HVAC systems and  $u$ -th option for the lighting system are chosen for retrofit, respectively. The values of  $e$ ,  $v$  and  $u$  integers are defined in (4.2)-(4.4).

$$e \in \{1, 2, \dots, (I + 1)(J + 1)\}, \quad (4.2)$$

$$v \in \{1, 2, \dots, (C + 1)(H + 1)\}, \quad (4.3)$$

$$u \in \{1, 2, \dots, (L_1 + 1)(L_2 + 1) \dots (L_m + 1)\}. \quad (4.4)$$

There is a strong coupling between the envelope and HVAC systems in their energy performance because the thermal performance of the envelope system affects the load of the HVAC system. As a consequence, these two subsystems are considered together in view of energy savings. In this case, there are  $(I + 1)(J + 1)(C + 1)(H + 1)$  retrofit options for the combined system. Let  $r$  defined in (4.5) denotes that the  $r$ -th option for the combined system, i.e., the  $e$ -th option for the envelope system and the  $v$ -th option for the HVAC systems, is chosen for the retrofit. The selection of the envelope, HVAC system and lighting system can thus be represented by the values of  $r$  and  $u$ .

$$r \in \{1, 2, \dots, (I + 1)(J + 1)(C + 1)(H + 1)\}. \quad (4.5)$$

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

### 4.3 OPTIMIZATION METHOD I

The first method solves the whole-building optimization problem considering all floors and all the relevant constraints of the project by assuming that the optimal retrofit options for each floor of the building are the same. For instance, if the  $e$ -th option for the envelope system, the  $v$ -th option for the HVAC system and the  $u$ -th option for the lighting system are chosen by the optimization model, each floor of the building will use these options for its retrofit. As the structure and functions of all the floors are the same, the optimization then determines the optimal retrofit options  $e$ ,  $v$ ,  $u$  and the number of floors to retrofit their subsystems with these optimally selected options. In addition, the optimization will, at the same time, determine the option for the PV system, the number of PV panels to be installed, and the solution for the roof retrofit optimally.

#### 4.3.1 Decision variables

The decision variable of the building retrofit optimization problem following the first method is given by

$$X_1 = [r, u, N_f^{env}, N_f^{lig}, k, p, N_p^0],$$

where  $N_f^{env}$  denotes the number of floors to retrofit the envelope system and  $N_f^{lig}$  denotes the number of floors to retrofit the lighting system.  $k \in \{1, 2, \dots, (K + 1)\}$  and  $p \in \{1, 2, \dots, (P + 1)\}$  mean that the  $k$ -th roof alternative is chosen for retrofit and the  $p$ -th solar panel alternative is to be used for the PV system installation, respectively.

#### 4.3.2 Objectives

The objectives of the building retrofit project include energy savings and the payback period.

The energy savings of the building retrofit project in year  $t$ ,  $ES_1(t)$  can be calculated by equation (4.6):

$$ES_1(t) = N_f^{env} ES^{mix}(r) + (F - N_f^{env}) ES^{mix}(r - e + 1) + N_f^{lig} ES^{lig}(u) + ES^{rof}(k, v) + ES^{pv}(p) N_p^0, \quad (4.6)$$

where  $ES^{mix}(r)$  is the energy savings of retrofitting one floor's envelope and the building's HVAC system with the  $r$ -th option measured in Wh,  $ES^{lig}(u)$  is the energy savings of retrofitting one floor's

lighting system with the  $u$ -th option measured in Wh,  $ES^{rof}(k, v)$  is the energy savings of retrofitting the roof of the building with its  $k$ -th option when the HVAC system is retrofitted with its  $v$ -th option, measured in Wh and  $ES^{pv}(p)$  is the energy production of one solar panel of the  $p$ -th option measured in Wh. The second term in (4.6) represents the energy savings achieved by retrofitting the centralized HVAC system on the floors whose envelope systems are not retrofitted.

Taking into account the discount rate and the tax incentive program mentioned in Chapter 3, the payback period of the building retrofit project  $T_{p1}$  can be calculated with the general formulas (4.7)-(4.9):

$$T_p = M + \frac{|\bar{C}_f(M)|}{C_f(M+1)}, \quad (4.7)$$

$$C_f(t) = \frac{p(t)ES(t) + R(t)}{(1+d)^t} - C_r, \quad (4.8)$$

$$R(t) = (E_{tot}(t-1) - E_{tot}(t))\zeta_a \zeta_t, \quad (4.9)$$

where  $T_p$ ,  $ES(t)$  and  $C_r$  are replaced by  $T_{p1}$ ,  $ES_1(t)$  and  $C_{r1}$  defined as

$$C_{r1} = N_f^{env}(C^{mix}(r) - C^{hva}(v)) + N_f^{lig}C^{lig}(u) + C^{rof}(k) + C^{pv}(p)N_p^0 + C^{hva}(v). \quad (4.10)$$

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

### 4.3.3 Objective function

The purpose of the optimization problem for the building retrofit is to maximize the energy savings and minimize the payback period of the building retrofit project. With the weighted sum method, the objective function is formulated into equation (4.11):

$$J = -w_1 \sum_{t=1}^T ES_1(t) + w_2 T_{p1}. \quad (4.11)$$

### 4.3.4 Constraints

The budget limit for the retrofit is described by

$$C_{r1} \leq \beta. \quad (4.12)$$

The EPC rating limit is described by

$$E_p < \delta E_r, \quad (4.13)$$

where

$$E_p = \frac{E_{tot}}{A_g}. \quad (4.14)$$

The physical limits include the area limit and design limit. The area limit implies that the size of the PV system to be installed should not exceed the available area of the roof, which can be described by the following general formula (4.15):

$$A^{pv}(p)N_p^0 \leq A_{eff}, \quad (4.15)$$

where  $A^{pv}(p)$  is the area of one solar panel of the  $p$ -th option.

All the decision variables must satisfy the integer constraints (4.16):

$$\left\{ \begin{array}{l} N_f^{emv} \in \{0, 1, \dots, F\} \\ N_f^{lig} \in \{0, 1, \dots, F\} \\ r \in \{1, 2, \dots, (I+1)(J+1)(C+1)(H+1)\} \\ u \in \{1, 2, \dots, (L1+1)(L2+1) \dots (Lm+1)\} \\ k \in \{1, 2, \dots, (K+1)\} \\ p \in \{1, 2, \dots, (P+1)\} \end{array} \right. . \quad (4.16)$$

#### 4.4 OPTIMIZATION METHOD II

Based on optimization method I, one will naturally think of a second method, which might make greater use of investments to find better optimal retrofit plans at the same time of reducing the complexity of the optimization problem in Chapter 3. In this section, optimization method II is proposed. Compared with method I, the difference is that optimization method II makes it possible for each floor to have different retrofit options for a kind of subsystem, i.e., the same subsystem of all floors can be retrofitted with different options. In addition, each floor of the building can be considered separately to determine whether its subsystems are to be retrofitted or not. Therefore, the second optimization method is to compile an optimal retrofit plan for the whole-building retrofit within a given budget by determining the retrofit states and retrofit options for the energy consuming subsystems of each floor and the roof

system of the building, the installation option for the PV system and the number of solar panels to be installed.

#### 4.4.1 Decision variables

The decision variable of the building retrofit optimization following the second method given here is given by

$$X_2 = [v, e_1, \dots, e_f, \dots, e_F, u_1, \dots, u_f, \dots, u_F, k, p, N_p^0],$$

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

#### 4.4.2 Objectives

The objectives of the optimization problem, including energy savings and the payback period, are calculated as follows.

The energy savings of the building retrofit project in year  $t$ ,  $ES_2(t)$  can be calculated by (4.17)

$$ES_2(t) = \sum_{f=1}^F (ES^{mix}(v, e_f) + ES^{lig}(u_f)) + ES^{rof}(k, v) + ES^{pv}(p)N_p^0, \quad (4.17)$$

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

The payback period of the building retrofit project  $T_{p2}$  can be calculated with the general formulas (4.7)-(4.9) where  $ES(t)$  and  $C_r$  are replaced by  $ES_2(t)$  and  $C_{r2}$  defined as

$$C_{r2} = \sum_{f=1}^F [C^{mix}(v, e_f) - C^{hva}(v) + C^{lig}(u_f)] + C^{rof}(k) + C^{pv}(p)N_p^0 + C^{hva}(v), \quad (4.18)$$

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



### 4.4.3 Objective function

The objective function of this method is given by (4.19).

$$J = -w_1 \sum_{t=1}^T ES_2(t) + w_2 T_{p2}. \quad (4.19)$$

### 4.4.4 Constraints

The budget limit can be described by:

$$C_{r2} \leq \beta. \quad (4.20)$$

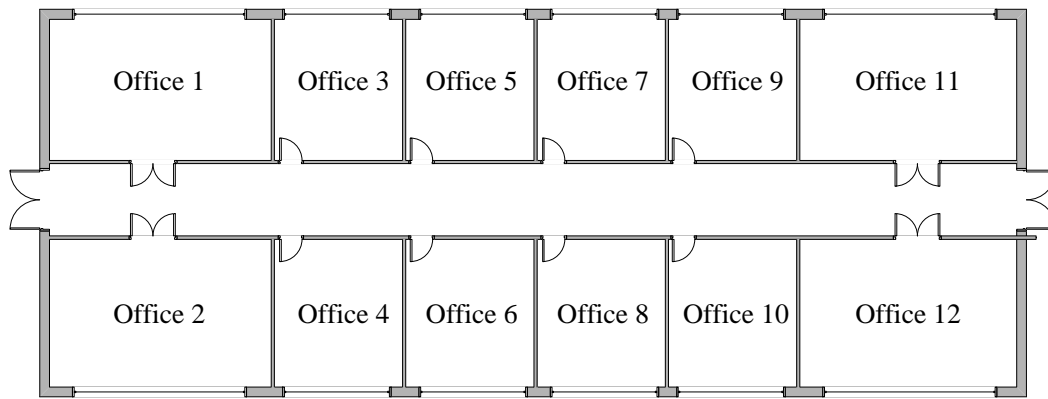
The EPC rating limit can be described with the formulas (4.13)-(4.14). The PV installation area limit is described by formulas (4.15). The limits on the design variables are:

$$\left\{ \begin{array}{l} v \in \{1, 2, \dots, (C+1)(H+1)\} \\ e_f \in \{1, 2, \dots, (I+1)(J+1)\}, \forall f \in \{1, 2, \dots, F\} \\ u_f \in \{1, 2, \dots, (L_1+1)(L_2+1) \dots (L_m+1)\}, \forall f \in \{1, 2, \dots, F\} \\ k \in \{1, 2, \dots, (K+1)\} \\ p \in \{1, 2, \dots, (P+1)\} \end{array} \right. \quad (4.21)$$

## 4.5 CASE STUDY

### 4.5.1 Case information

In this section, an existing office building is used as a case study to verify the viability of the two optimization models proposed in this chapter for building retrofit planning. The building has six floors with the same structure, which is shown in Fig. 4.1. The area of each floor is 266 m<sup>2</sup>. Before the retrofit, the EPC rating of the building under study is grade E. Therefore, this building has to improve its energy efficiency to achieve at least a D rating by implementing energy-efficient interventions in order to comply with the green building policy.



**Figure 4.1.** Structure of one floor of the office building under study

The information of the alternatives for retrofitting the envelope, lighting, HVAC and roof systems and installing the PV system are detailed in Tables 4.1-4.7. Table 4.7 gives the information on the alternative lighting technologies used to retrofit the corresponding existing lighting technologies. The economic parameters involved in the optimization models include the discount rate and the increase rate of the electricity price, which are determined as 6% and 12.69%, respectively, according to South Africa's economic statistics and Eskom.

**Table 4.1.** Window alternatives

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

**Table 4.2.** Wall insulation material alternatives

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

**Table 4.3.** Roof insulation material alternatives

$k$	Alternatives	$d_k(\text{m})$	$\lambda_k(\text{W/m}^\circ\text{C})$	$C_k^{rof}(\$/\text{m}^2)$
1	SPF	0.020	0.042	8.23
2	EPS	0.060	0.033	10.49
3	Stone wool	0.105	0.037	44.84

**Table 4.4.** Chiller alternatives

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

**Table 4.5.** Heat pump alternatives

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

**Table 4.6.** Solar panel alternatives

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

#### 4.5.2 Data collection

Referring to Section 4.2, there are 144 retrofit options for the envelope and HVAC systems together, 64 retrofit options for the lighting system, 36 retrofit options for the roof considering the HVAC system and four installation options for the PV system.

The notch test data obtained through the M&V process are detailed in Tables 4.8-4.11. To be specific, the energy savings and cost of retrofitting the envelope system of one floor and the HVAC system of

**Table 4.7.** Lighting technology alternatives

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

the building with different combined options are detailed in Table 4.8. For example, the fifth row in Table 4.8 (part 2) details the 38-th retrofit option for the envelope and HVAC systems, which implies that the chiller in the HVAC is not retrofitted, the heat pump is retrofitted with its second alternative, the windows are replaced with their first alternative and the walls are installed with their first insulation alternative. Retrofitting the envelope system of one floor and the HVAC system of the building using this option results in 2677 kWh of energy savings on the floor at a cost of \$13425.

The results of retrofitting the lighting system of one floor with different options are detailed in Table 4.9. For example, the 32-nd row in Table 4.9 (part 1) gives the detailed information of the 31-st retrofit option for the lighting system, which means that the three types of lighting technologies are retrofitted with the first, third and second of their corresponding alternatives, respectively. As a result, 23737 kWh of energy can be saved by applying the retrofit option at a cost of \$4108.

The results of retrofitting the roof of the building, considering the retrofit situation of the HVAC system, are detailed in Table 4.10. For example, the 23-rd row in Table 4.10 (part 1) indicates the energy savings and cost of retrofitting the roof system with the first insulation alternative listed in Table 4.3 with the situation of the chiller and heat pump in the HVAC system of the building being

**Table 4.8.** Notch test data of retrofitting a floor's envelope and the building's HVAC system (part 1)

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

**Table 4.8.** Notch test data of retrofitting a floor's envelope and the building's HVAC system (part 2)

$r(v,e)$	Chiller	Heat pump	Window	Wall	$ES^{mix}(r)$ (kWh)	$C^{mix}(r)$ (\$)
35	0	2	0	2	314	10714
36	0	2	0	3	318	18240
37	0	2	1	0	2646	10881
38	0	2	1	1	2677	13425
39	0	2	1	2	2681	14170
40	0	2	1	3	2684	21696
41	0	2	2	0	2270	12955
42	0	2	2	1	2301	15499
43	0	2	2	2	2305	16244
44	0	2	2	3	2308	23770
45	0	2	3	0	2396	14130
46	0	2	3	1	2427	16674
47	0	2	3	2	2431	17419
48	0	2	3	3	2434	24945
49	1	0	0	0	4870	8580
50	1	0	0	1	4924	11124
51	1	0	0	2	4930	11869
52	1	0	0	3	4937	19395
53	1	0	1	0	5391	12036
54	1	0	1	1	5445	14580
55	1	0	1	2	5452	15325
56	1	0	1	3	5458	22851
57	1	0	2	0	5315	14110
58	1	0	2	1	5369	16654
59	1	0	2	2	5376	17399
60	1	0	2	3	5382	24925
61	1	0	3	0	5342	15285
62	1	0	3	1	5396	17829
63	1	0	3	2	5402	18574
64	1	0	3	3	5409	26100
65	1	1	0	0	5160	16500
66	1	1	0	1	5177	19044
67	1	1	0	2	5179	19789
68	1	1	0	3	5181	27315

**Table 4.8.** Notch test data of retrofitting a floor's envelope and the building's HVAC system (part 3)

$r(v,e)$	Chiller	Heat pump	Window	Wall	$ES^{mix}(r)$ (kWh)	$C^{mix}(r)$ (\$)
69	1	1	1	0	5655	19956
70	1	1	1	1	5671	22500
71	1	1	1	2	5673	23245
72	1	1	1	3	5675	30771
73	1	1	2	0	5577	22030
74	1	1	2	1	5594	24574
75	1	1	2	2	5596	25319
76	1	1	2	3	5598	32845
77	1	1	3	0	5604	23205
78	1	1	3	1	5620	25749
79	1	1	3	2	5622	26494
80	1	1	3	3	5624	34020
81	1	2	0	0	5149	16005
82	1	2	0	1	5167	18549
83	1	2	0	2	5169	19294
84	1	2	0	3	5171	26820
85	1	2	1	0	5645	19461
86	1	2	1	1	5663	22005
87	1	2	1	2	5665	22750
88	1	2	1	3	5667	30276
89	1	2	2	0	5568	21535
90	1	2	2	1	5586	24079
91	1	2	2	2	5588	24824
92	1	2	2	3	5590	32350
93	1	2	3	0	5594	22710
94	1	2	3	1	5612	25254
95	1	2	3	2	5614	25999
96	1	2	3	3	5616	33525
97	2	0	0	0	4701	7590
98	2	0	0	1	4756	10134
99	2	0	0	2	4762	10879
100	2	0	0	3	4769	18405
101	2	0	1	0	5288	11046
102	2	0	1	1	5342	13590

**Table 4.8.** Notch test data of retrofitting a floor's envelope and the building's HVAC system (part 4)

$r(v,e)$	Chiller	Heat pump	Window	Wall	$ES^{mix}(r)$ (kWh)	$C^{mix}(r)$ (\$)
103	2	0	1	2	5349	14335
104	2	0	1	3	5355	21861
105	2	0	2	0	5201	13120
106	2	0	2	1	5256	15664
107	2	0	2	2	5262	16409
108	2	0	2	3	5269	23935
109	2	0	3	0	5231	14295
110	2	0	3	1	5286	16839
111	2	0	3	2	5292	17584
112	2	0	3	3	5299	25110
113	2	1	0	0	4992	15510
114	2	1	0	1	5009	18054
115	2	1	0	2	5011	18799
116	2	1	0	3	5013	26325
117	2	1	1	0	5551	18966
118	2	1	1	1	5568	21510
119	2	1	1	2	5570	22255
120	2	1	1	3	5572	29781
121	2	1	2	0	5463	21040
122	2	1	2	1	5481	23584
123	2	1	2	2	5483	24329
124	2	1	2	3	5485	31855
125	2	1	3	0	5493	22215
126	2	1	3	1	5510	24759
127	2	1	3	2	5512	25504
128	2	1	3	3	5514	33030
129	2	2	0	0	4981	15015
130	2	2	0	1	4999	17559
131	2	2	0	2	5001	18304
132	2	2	0	3	5004	25830
133	2	2	1	0	5541	18471
134	2	2	1	1	5560	21015
135	2	2	1	2	5562	21760
136	2	2	1	3	5564	29286



**Table 4.8.** Notch test data of retrofitting a floor's envelope and the building's HVAC system (part 5)

$r(v,e)$	Chiller	Heat pump	Window	Wall	$ES^{mix}(r)$ (kWh)	$C^{mix}(r)$ (\$)
137	2	2	2	0	5454	20545
138	2	2	2	1	5472	23089
139	2	2	2	2	5474	23834
140	2	2	2	3	5477	31360
141	2	2	3	0	5483	21720
142	2	2	3	1	5502	24264
143	2	2	3	2	5504	25009
144	2	2	3	3	5506	32535

retrofitted with the first alternative listed in Table 4.4 and the second alternative listed in Table 4.5, respectively. Retrofitting the roof system with this option leads to 131 kWh of energy savings at a cost of \$2189.

The results of installing a PV system with different options are detailed in Table 4.11. For example, the third row in Table 4.11 means one solar panel can result in 393 kWh of energy savings at a cost of \$593 when the second installation option for the PV system is chosen.

In this study, the building retrofit optimization problem is solved by a genetic algorithm. To investigate the impact of investments on the optimal retrofit plans, the results of applying the optimal plans obtained by the two optimization models proposed in Section 4.2 with different budgets are detailed in the following sections. During the optimization processes, the budgets are set at \$10000, \$25000, \$45000 and \$200000, respectively. As the two optimization models give decision makers or project managers a convenient method to obtain a desired retrofit plan satisfying their preferences by tuning the weighting factors, the effectiveness of tuning the weighting factors is also studied. In addition, the tax incentive program in South Africa is taken into account in the models. Therefore, the impact of the tax incentive on the optimal retrofit plan is also analyzed.

**Table 4.9.** Notch test data of retrofitting the lighting system of one floor (part 1)

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

**Table 4.9.** Notch test data of retrofitting the lighting system of one floor (part 2)

u	Light 1	Light 2	Light 3	$ES^{lig}(u)$ (kWh)	$C^{lig}(u)$ (\$)
35	2	0	2	17533	3050
36	2	0	3	17257	2711
37	2	1	0	16900	2841
38	2	1	1	25010	5385
39	2	1	2	24549	4537
40	2	1	3	24273	4198
41	2	2	0	16053	2913
42	2	2	1	24163	5457
43	2	2	2	23702	4609
44	2	2	3	23426	4269
45	2	3	0	15327	2512
46	2	3	1	23437	5056
47	2	3	2	22977	4208
48	2	3	3	22700	3869
49	3	0	0	6463	663
50	3	0	1	14573	3207
51	3	0	2	14112	2359
52	3	0	3	13836	2019
53	3	1	0	13478	2149
54	3	1	1	21588	4693
55	3	1	2	21128	3845
56	3	1	3	20851	3506
57	3	2	0	12632	2221
58	3	2	1	20742	4765
59	3	2	2	20281	3917
60	3	2	3	20004	3578
61	3	3	0	11906	1820
62	3	3	1	20016	4364
63	3	3	2	19555	3516
64	3	3	3	19279	3177

**Table 4.10.** Notch test data of retrofitting the roof considering the HVAC retrofit (part 1)

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

**Table 4.10.** Notch test data of retrofitting the roof considering the HVAC retrofit (part 2)

v,k	Chiller	Heat pump	Roof	$ES^{rof}(k)$ (kWh)	$C^{rof}(k)$ (\$)
35	2	2	2	142	2790
36	2	2	3	144	11927

**Table 4.11.** Notch test data of installing one solar panel

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

### 4.5.3 Results analysis of optimization method I

This part provides the results of applying the optimal retrofit plans obtained by optimization I. In addition, the impacts of investments, weighting factors and the tax incentive program on the building retrofit project are investigated.

To verify the feasibility of the first optimization method for building retrofit planning, the optimal retrofit actions with different budgets based on the method and the results of applying the plans obtained are detailed in Table 4.12.

In Table 4.12, the detailed retrofit actions for the building with different investments are provided.  $r$  represents the retrofit options for the envelope system of each floor and the HVAC system of the building.  $u$  represents the retrofit option for the lighting system of each floor.  $N_f^{env}$  and  $N_f^{lig}$  indicate the number of floors to retrofit their envelope systems and lighting systems, respectively.  $(v, k)$  represents the retrofit options listed in Table 4.10 for the roof system of the building, considering the retrofit state of the HVAC system.  $p$  and  $N_p^0$  represent the installation option listed in Table 4.11 for the PV power supply system and the number of solar panels to be installed, respectively. The optimal retrofit plans for the building with different investments are indicated by the numbers in the last four columns from the fourth to the tenth row of the table. For instance, the number '85' for  $r$  means that the 85-th option for the envelope system and the HVAC system is chosen for retrofit with a budget of \$200000. The

**Table 4.12.** Results of applying optimization method I with different budgets

	Budget 1	Budget 2	Budget 3	Budget 4
$\beta$ (\$)	10000	25000	45000	200000
$C_{r1}$ (\$)	9263	24586	44683	196490
$r$	1	1	49	85
$N_f^{env}$	0	0	0	2
$u$	52	24	23	22
$N_f^{lig}$	4	6	6	6
$(v, k)$	1	1	13	21
$p$	2	2	2	3
$N_p^0$	2	0	16	163
$T_{p1}$ (month)	22	22	27	59
$ES_1$ (kWh)	561286	1501978	1873954	2530403
$ES_p$	17%	45%	56%	75%
$E_p$	0.927	0.617	0.494	0.278
RSD of $T_{p1}$	2.67%	2.65%	0.83%	3.55%
RSD of $ES_1$	3.40%	4.46%	0.14%	0.16%
RSD of $E_p$	0.68%	3.29%	0.18%	0.48%

number ‘49’ for  $r$  means the 49-th option is chosen, which indicates that the envelope systems of the building are not retrofitted and only the HVAC system of the building is retrofitted with the budget of \$45000. ‘2’ for  $N_f^{env}$  means that the envelope systems of two floors of the building are retrofitted. The number ‘23’ for  $u$  and ‘6’ for  $N_f^{lig}$  in the third column represent that the lighting systems of all six floors are retrofitted with the 23-rd option with a budget of \$45000. The numbers ‘13’ and ‘21’ for  $(v, k)$  both represent that the roof system of the building is not retrofitted, referring to Table 4.10. The numbers ‘2’ for  $p$  and ‘16’ for  $N_p^0$  in the third column mean that the second option in Table 4.11 is chosen for setting up the PV system and seven of the selected solar panels are installed.

The items  $ES_1$  and  $T_{p1}$  represent the resulting energy savings and payback period of the building retrofit project making use of optimization method I. It can be seen that the energy savings and payback period keep increasing with growing budgets. The reason for this phenomenon is that more investments allow more systems to be retrofitted, thus resulting in more energy savings and a longer payback period. Moreover, one can see that the growth rate of the payback period increases with growing budgets. This is because more and more systems with long payback periods are retrofitted when the budget

increases. For instance, only the lighting systems are retrofitted with the budget of \$25000. However, 16 solar panels are installed in addition to the lighting system with a budget of \$45000. When the budget increases to \$200000, more solar panels are installed and the envelope systems of some floors are retrofitted.

In the table, an interesting phenomenon is that the payback period with a budget of \$10000 is almost the same as that with a budget of \$25000. This can be explained by the cost-effectiveness of retrofitting different subsystems with different options. Retrofitting the lighting system is a most cost-effective method to save energy and is followed by retrofitting the HVAC system. Installing a PV system and retrofitting the envelope system have long payback periods. With a budget of \$25000, all the investment is used to retrofit the lighting systems, while part of the investment is used to install a PV system with the budget of \$10000. In addition, the 24-th option chosen for retrofitting the lighting systems with the budget of \$25000 is more energy-efficient compared with the 52-nd one and results in a relatively shorter payback period. That is why the payback periods of the two budgets are almost the same.

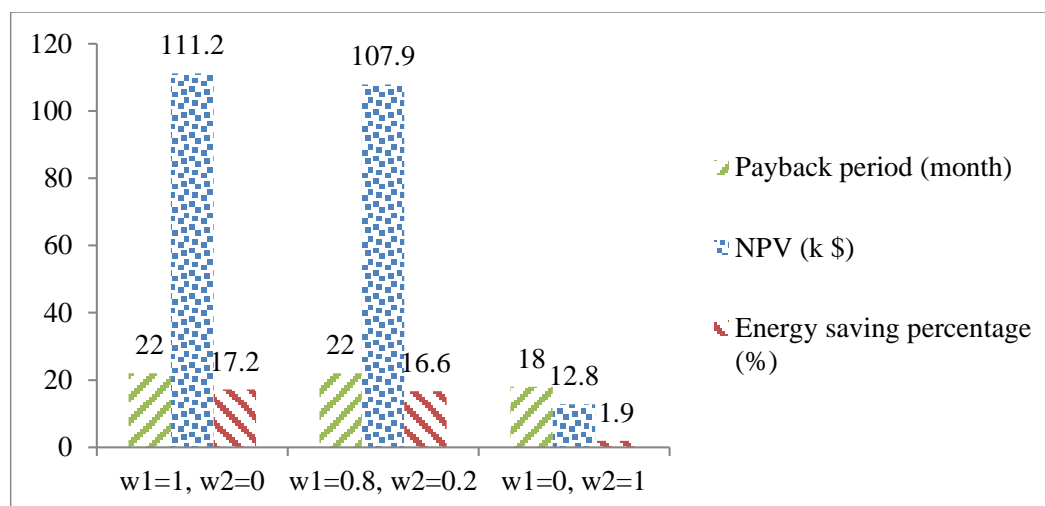
The optimal retrofit actions for the building retrofit project with different budgets are reflected in the last four columns from the fourth to 18-th row in the table. It can be seen that the lighting systems of four floors of the building are retrofitted with the 52-nd option and two solar panels of its second option in Table 4.11 are installed with the budget of \$10000. However, the lighting systems of all the floors are retrofitted while no PV panels are installed with the budget of \$25000. When the investment grows to \$45000, all the lighting systems of the building are retrofitted with a more energy-efficient option and the HVAC system is also retrofitted. In addition, 16 solar panels of the second option are installed. With the budget of \$200000, the envelope systems of some floors are considered to be retrofitted in addition to selecting better options for other subsystems to be retrofitted and installing more solar panels. In view of the above phenomenon, the conclusion can be reached that the investment gives priority to the subsystems of the building in the order of the lighting, HVAC, PV, envelope and roof. This is because retrofitting the lighting systems is the most cost-effective choice to save energy, followed by the HVAC system. When retrofitting the envelope and roof systems and installing a PV power supply system, it takes a long time to pay back the cost in spite of great energy savings.

One of the purposes of this chapter is to improve the energy efficiency of the building to achieve a good EPC rating for green building policy compliance. In Table 4.12,  $E_p$  represents the energy intensity of the building after applying the optimal retrofit plan obtained from optimization method I. Compared

with the reference value in Table 3.1, the four optimal retrofit plans obtained with budgets of \$10000, \$25000, \$45000 and \$200000 can help the building to get a D, C, B and A EPC rating, respectively. In addition, the table shows that 2530.4 MWh of energy savings can be achieved with a payback of 59 months with optimization method I. This demonstrates the feasibility of the method for building retrofit planning aimed at saving energy in the most cost-effective way and complying with the green building policy.

In Table 4.12, the RSD of items  $T_{p1}$ ,  $ES_1$  and  $E_p$  represents the relative standard deviations (RSD) of the payback period, energy savings of the building retrofit project and the energy intensity of the building achieved by retrofit, respectively. The values of these items' RSD are less than 5%, which means the results obtained with optimization method I are stable.

The optimization problem for building retrofit is solved with the weighted sum method. This enables decision makers or project managers to obtain a desired optimal retrofit plan according to their preference for optimizing either the energy savings or payback period by tuning the weighting factors. To verify this, the optimization problem is solved again by optimization method I with two more sets of weighting factors. For convenience of comparison, other factors that affect the retrofit project remain the same. For instance, the budgets are the same, namely \$10000, and the tax incentive program is taken into account during the optimization process. The results of applying the optimal retrofit plans obtained with different weighting factors are presented in Fig. 4.2. In Fig. 4.2, it can be seen that



**Figure 4.2.** Optimal results obtained by optimization method I with different weighting factors

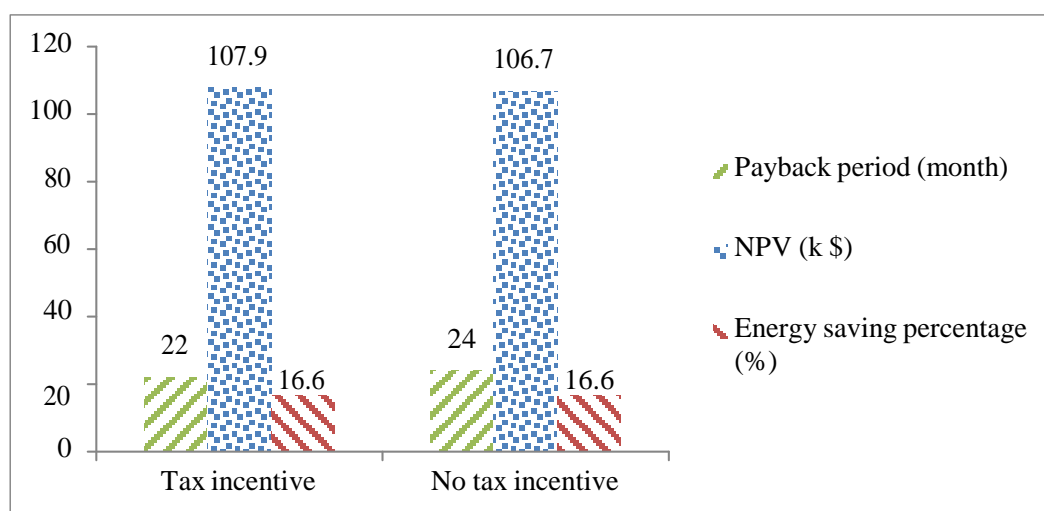
the energy savings increase while the payback period decreases when their corresponding weighting



factors grow. For instance, the percentage of energy savings of the building retrofit project increases from 1.9% to 17.2% when the value of its corresponding weighting factor  $w_1$  changes from zero to one. The changing trend of NPV is the same as that of the energy savings. The payback period of the project decreases from 22 months to 18 months when the value of its corresponding weighting factor  $w_2$  changes from zero to one.

In view of the comparison above, one can see that changing the weighting factor for energy savings has a significant effect on the energy savings of the building retrofit project. This is because only the lighting systems are considered to be retrofitted with the budget of \$10000 and retrofitting lighting systems is the most cost-effective in saving energy, which also explains why the payback period does not change much when its weighting factor changes.

To investigate the impact of the tax incentive program on the building retrofit project, the optimization problem is solved by optimization method I without considering the tax incentive. During the optimization process, the values of the weighting factors and the budget are set to  $w_1 = 0.8$ ,  $w_2 = 0.2$  and \$10000, which are the same as those in the situation where the tax incentive is considered. The results are presented in Fig. 4.3. Fig. 4.3 illustrates that considering the tax incentive program in



**Figure 4.3.** Impact of tax incentive on the optimal results obtained by optimization method I with  $w_1 = 0.8$ ,  $w_2 = 0.2$ ,  $\beta = \$10000$

the optimization process results in a shorter payback period and more NPV. For instance, the figure shows that the payback period increases by about two months and the NPV decreases by \$1200 with a

budget of \$10000, compared with the results considering the tax incentive. Therefore, the tax incentive program has little influence on the building retrofit project.

#### 4.5.4 Results analysis of optimization method II

This part provides the results of applying the optimal retrofit plans obtained by optimization method II. The impacts of investments, weighting factors and the tax incentive program on the building retrofit project are investigated in detail.

To verify the feasibility of optimization method II for building retrofit planning, the optimal retrofit outcomes obtained with different budgets based on the method and the results of applying the achieved plans are detailed in Table 4.13.

In Table 4.13, the items  $r_1, r_2, r_3, r_4, r_5$  and  $r_6$  represent the retrofit options from Table 4.8 for the envelope systems of the six floors and the HVAC system of the building.  $u_1, u_2, u_3, u_4, u_5$  and  $u_6$  represent the retrofit options from Table 4.9 for the lighting systems of the six floors. The optimal retrofit outcomes obtained with different weighting factors for the building are indicated by the numbers in the last four columns from the fourth to the 18-th row of the table. For instance, the number ‘69’ for  $r_3$  in the last column means that the HVAC system of the building and the envelope system of the third floor are retrofitted with the 69-th option with a budget of \$200000. The number ‘49’ for  $r_3$  in the second column has the same meaning, but indicates that the envelope of the third floor will not be retrofitted and only the HVAC system of the building is retrofitted with a budget of \$25000. The numbers ‘1’ for  $u_2$  and ‘64’ for  $u_4$  in the second column represent that the lighting system of the second floor is not retrofitted, while that of the fourth floor is retrofitted with the 22-nd option with a budget of \$10000. The numbers ‘1’, ‘13’, and ‘17’ for  $(v, k)$  all indicate that the roof system is retrofitted. The numbers ‘2’ for  $p$  and ‘17’ for  $N_p^0$  in the third column mean that the second option is chosen for the PV system installation and 17 solar panels are to be installed. According to the results in 4.13, one can see that optimization method II allows each floor to be different in the retrofit options for its subsystems. For instance, option 23 is chosen for one floor, while for the other five floors option 22 is chosen for retrofitting the lighting systems with the budget of \$200000.

Items  $ES_2$  and  $T_{p2}$  in Table 4.13 represent the resulting energy savings and payback period of the

**Table 4.13.** Results of applying optimization method II with different budgets

	Budget 1	Budget 2	Budget 3	Budget 4
$\beta$ (\$)	10000	25000	45000	200000
$C_{r2}$ (\$)	9860	24925	44936	199593
$r_1$	1	1	49	69
$r_2$	1	1	49	65
$r_3$	1	1	49	69
$r_4$	1	1	49	65
$r_5$	1	1	49	65
$r_6$	1	1	49	69
$u_1$	56	23	23	23
$u_2$	1	24	23	22
$u_3$	1	24	24	22
$u_4$	64	24	23	22
$u_5$	1	24	23	22
$u_6$	64	24	23	22
$(v, k)$	1	1	13	17
$p$	4	2	2	3
$N_p^0$	0	0	17	163
$T_{p2}$ (month)	22	22	27	60
$ES_2$ (kWh)	594086	1504742	1875121	2531403
$ES_p$	18%	45%	56%	75%
$E_p$	0.916	0.616	0.494	0.277
RSD of $T_{p2}$	2.00%	1.95%	3.55%	2.69%
RSD of $ES_2$	1.74%	3.47%	3.64%	0.64%
RSD of $E_p$	0.36%	2.54%	3.62%	1.79%

building retrofit project making use of optimization method II. It can be seen that the energy savings and payback period keep growing when the budgets increase. In Table 4.13, one can see that the payback periods of the building retrofit project with the budgets of \$10000 and \$25000 are almost the same. This is because there is not enough investment to retrofit the lighting systems with options that are more energy-efficient when using the budget of \$10000. Although the retrofit plan obtained with the budget of \$25000 costs much more than that with the budget of \$10000, the plan entails the implementation of options 23 and 24, which are more energy-efficient compared with options 56 and 64.

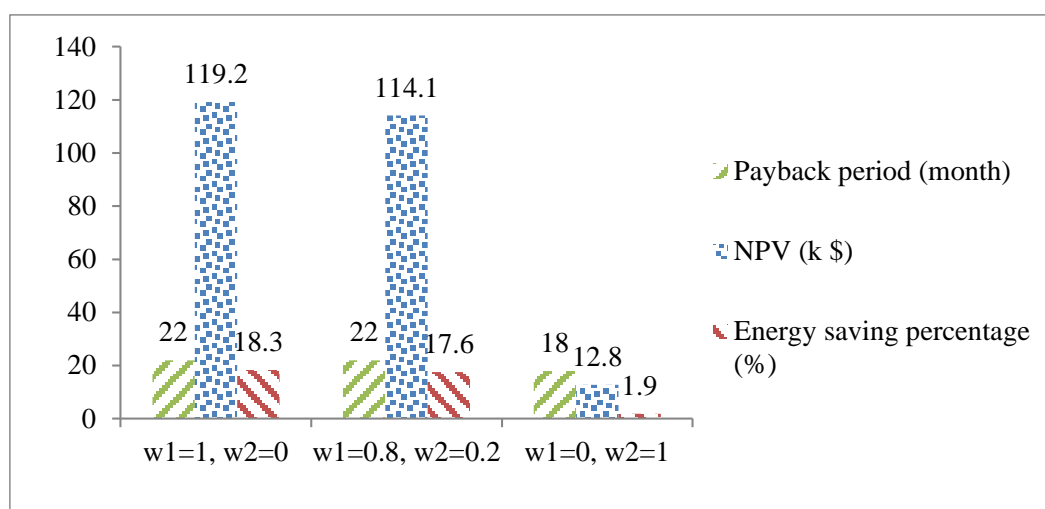
According to the relationship between the optimal retrofit plans and the budgets, the table makes the same point as Table 4.12, which is that retrofitting the lighting and HVAC systems of a building in a retrofit project should be considered first. If the investment is sufficient, retrofitting the envelope and installing a PV system can then be considered. For instance, all the investments are used to retrofit the lighting systems of the building with budgets of \$10000 and \$25000. When the budget increases to \$45000, the HVAC system is retrofitted and a PV system is installed with 17 solar panels of the second option. Except for these systems, the envelope system is retrofitted with the budget of \$200000. Only the envelope systems of three floors are retrofitted while all the other systems are fully retrofitted. In addition, the roof system of the building is not retrofitted. Therefore, the envelope and roof systems are the last to be considered for retrofit. Another phenomenon showing the investor's retrofit preferences is that the investor prefers to keep changing the retrofit options for the lighting and HVAC systems to more energy-efficient ones before considering retrofitting other systems. For instance, the options for the lighting system change from 56 and 64, to 23 and 24, and then to 22 and 23 when the budget grows from \$10000 to \$200000. In addition, the retrofit options for the HVAC system of the building are changed to better ones.

Table 4.12 also shows that the energy efficiency of the building after retrofit is improved effectively. For instance, the energy intensity of the building is improved to 0.916, 0.616, 0.494 and 0.277 with budgets of \$10000, \$25000, \$45000 and \$200000, respectively. That is to say, the optimal retrofit plans obtained by optimization method II can help the building to get a D, C, B and A rating from the EPC standard with those budgets.

In Table 4.12, one can see that the RSD of the payback period, energy savings of the building retrofit project and the energy intensity of the building achieved by retrofit are less than 5%, which verifies the stability of optimization method II in finding the optimal retrofit plans for buildings.

The optimization problem is solved again with two more sets of weighting factors to investigate the impact of weighting factors on the building retrofit project. During the optimization process, the budgets are the same, namely \$10000, and the tax incentive program is taken into account. The results of applying the optimal retrofit plans obtained with different weighting factors are presented in Fig. 4.4.

In Fig. 4.4, one can see that the energy savings and NPV increase while the payback period decreases



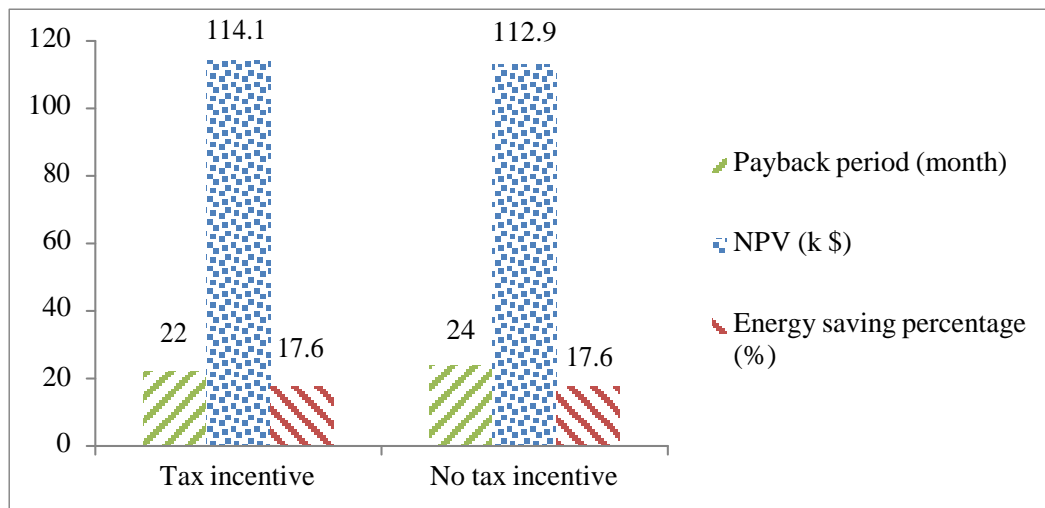
**Figure 4.4.** Optimal results obtained by optimization method II with different weighting factors

when their corresponding weighting factors grow. For instance, the payback period of the project decreases from 22 months to 18 months when the value of its corresponding weighting factor  $w_2$  changes from zero to one. The percentage of energy savings of the project increases from 1.9% to 18.3% when the value of its corresponding weighting factor  $w_1$  changes from zero to one.

In summary, decision makers or project managers are able to achieve a desired retrofit plan for building retrofit projects according to their preferences by tuning the weighting factors in the objective function.

The optimization problem is solved again without taking the tax incentive into account to investigate the impact of tax incentive. During the optimization process, the factors affecting the project are kept the same, namely  $w_1 = 0.8$ ,  $w_2 = 0.2$  and a budget of \$10000. The results are presented in Fig. 4.5.

In Fig. 4.5, one can see that the achieved NPV is more and the payback period is longer when the tax incentive program is not taken into account in the optimization model. For instance, the payback period increases by about two months and the NPV decreases by \$1200 with a budget of \$10000.



**Figure 4.5.** Impact of tax incentive on the optimal results obtained by optimization method II with  $w_1 = 0.8$ ,  $w_2 = 0.2$ ,  $\beta = \$10000$

#### 4.5.5 Comparison of the two methods

According to the results analysis of the two optimization methods proposed in this study, one can conclude that both methods reduce the complexity of the building retrofit problem in Chapter 3 and are feasible and effective to determine optimal retrofit plans for buildings. However, the first optimization method can be termed the superior one for most circumstances. The reasons for this are detailed below.

Firstly, the results obtained by the two methods are very similar, although optimization method I limits the retrofit options for each kind of subsystem of the floors to be the same, while method II allows the retrofit options for all the subsystems in the building to be different, which can ensure better use of the investment compared with method I. This can be verified by dividing the  $C_r$  by  $\beta$  in Tables 4.12 and 4.13. The results show that 98.6%-99.8% of the investments with the method II is used, while 92.6%-99.3% is used with method I. In fact, the results in Tables 4.12 and 4.13 indicate that method II is better than method I, as the the optimal retrofit plans obtained by method II result in more energy savings. However, one can conclude that the difference between the results obtained with the two methods is ignorable. For instance, 1502.0 MWh of energy was saved with a payback period of 22 months by method I and 1504.7 MWh of energy was saved with the same payback period by method II when a budget of \$25000 was allocated. Therefore, the conclusion can be drawn that the effectiveness

of the two optimization methods in solving building retrofit problems is almost the same.

Secondly, the dimension of the optimization problem is much smaller for method I compared with method II, especially when a large number of floors are involved. There are only five decision variables in optimization model I. However, the number of decision variables ( $2F + 4$ ) in optimization model II is related to the number of floors in a building. When the number of floors increases, the number of decision variables of model I will remain unchanged while that of model II will increase rapidly. Therefore, it is much more difficult to solve the building retrofit problems with method II than that with method I. In addition, the solution obtained with method II might be very poor in the case of a large number of decision variables because of the inefficiency of existing algorithms to solve integer programming problems with a large dimension of variables.

In summary, method I is simpler and more effective when solving a building retrofit problem with a large number of floors involved. While from a theoretical point of view method II is more accurate and should perform better, the solution results obtained by it are very close to those of method I. The dimension of the problem following method II, however, grows linearly with the increase in the number of floors, which sometimes causes the existing algorithms to fail to find a solution to the optimization problem. On the other hand, the dimension of the problem following method I stays unchanged regardless of the size of the building considered. It is therefore concluded that method I is superior to method II in practical applications.

## 4.6 CONCLUSION

This chapter presents two optimization methods for building retrofit projects. Their purpose is to simplify the optimization model presented in Chapter 3 in order to reduce the difficulty of solving the building retrofit optimization problem. In the two simplified methods, the ‘notch test’ data, including the potential energy savings and cost of retrofitting the subsystems of a building, consisting of the lighting, roof, PV, envelope and HVAC systems, are collected. Based on the data, the optimization methods need to determine the subsystems of the building to be retrofitted and the retrofit options for them rather than work out the retrofit plans for every specific facility of the building. Therefore, the dimension of the optimization problem is reduced and consequently the difficulty of obtaining an optimal retrofit plan is reduced.

The aims of the two simplified models are the same as those of the model presented in Chapter 3, namely to maximize the energy savings and minimize the payback period of the building retrofit project as well as get a good EPC rating in order to comply with the green building policy in South Africa by improving the energy efficiency of the building. The results of a case study show that good energy savings can be obtained with an acceptable payback period, which demonstrates the feasibility and effectiveness of the simplified optimization models proposed for building retrofit projects. During the optimization processes based on the two models, the impact of the weighting factors and the tax incentive program on the building retrofit project is investigated. The results show that the two models provide decision makers or project managers with a convenient way of achieving a desired retrofit plan according to their preference for more energy savings or a shorter payback period by tuning the weighting factors in the objective function. It was concluded that the tax incentive program has little influence on the building retrofit project. Moreover, it was concluded that method I is superior to method II presented in this chapter.



# **CHAPTER 5 OPTIMAL MAINTENANCE PLAN FOR BUILDING ENVELOPE INSULATION SYSTEM AFTER RETROFIT**

## **5.1 INTRODUCTION**

In building envelope retrofit projects, installing an insulation system on the envelopes is a popular and widely used method to improve the energy efficiency of the buildings, because of insulation materials' ability to eliminate unnecessary heat loss in the cooling season and heat gain in the heating season [133]. This helps to reduce the energy consumption of the buildings and to provide more thermal comfort for occupants. However, insulation materials' ability to prevent heat transfer degrades over time owing to various environment factors, such as solar irradiation and air temperature, among others. Hence, a proper maintenance plan for the insulation system of buildings is important to ensure the energy performance of the buildings remains good and to promote the sustainable energy savings of building retrofit projects.

The thermal performance degradation of insulation materials and the corresponding maintenance planning for them after retrofit are usually neglected in literature. Studies on insulation materials focus on their influence and properties. The influence of insulation materials is mainly reflected in pollution reduction, energy savings, thermal comfort, financial benefits and so on [134, 135, 136, 137, 138]. With respect to the properties of insulation materials, these are mainly reflected in mechanical strength, fire protection, thermal resistivity, density and robustness, among others [139, 140, 141, 142].

In summary, a great deal of investigation on insulation materials has been done in literature. However, little attention has been paid to the performance degradation and maintenance planning for insulation

materials. As proper maintenance plans for insulation systems installed in buildings can prevent the energy efficiency of the buildings from keeping degenerating over time, this chapter proposes an optimization model for building envelope insulation system maintenance planning after retrofit following the general methodology for obtaining optimal maintenance plans presented in [52, 104]. The purpose of the proposed model is to maximize the energy and economic benefits with given investments by installing insulation in the building's envelope and doing proper maintenance of the insulation system after the retrofit.

In a general building, the walls, roof and windows bear primary responsibility for the energy performance of the envelopes as they are the main envelope components exposed to the environment. Hence, in the existing building studied in this chapter, it is considered to install insulation materials on its walls and roof, and to replace its existing windows with better alternatives in the retrofit process to improve the energy efficiency of its envelope. After that, the proposed optimization model provides optimal maintenance plans for the installed envelope insulation system to achieve sustainable energy and financial benefits of the project in view of the insulation performance degradation. Maintenance for the building envelope insulation system takes place several times during the whole project period according to the proposed model. During each maintenance activity, insulation materials of different thicknesses are added to the envelope components.

The added benefit of considering the performance degradation of insulation materials is that an accurate estimation of the energy savings and economic benefits of the building retrofit project can be obtained, which will help to overcome the hesitation of decision makers or potential investors.

The remainder of this paper includes four parts. The modeling process of the optimization problem is elaborated on in Section 5.2, followed by the formulation of the problem in Section 5.3. After that, a case study is analyzed in Section 5.4. Finally, conclusions are drawn in Section 5.5.

## **5.2 SYSTEM MODELING**

To calculate the energy savings of a building retrofit project, the energy balances of the building before and after retrofit must be modeled. In addition, the performance degradation of insulation materials must be modeled first in order to calculate the energy usage of the building accurately.

Details of the models involved in the optimization problem of this chapter are given in the following subsections.

### 5.2.1 Thermal performance decay model

As addressed in Section 5.1, applying insulation materials to the envelope of buildings can protect the buildings against the environment effectively because of insulation materials' heat insulation capacity, which would lead to the reduction of the total energy consumption of the buildings as well as the improvement of thermal comfort. In the market, there are a wide variety of insulating materials. For instance, sprayed polyurethane, fiberglass, aerogel blankets, etc., are common insulation materials. In particular, sprayed polyurethane has been popular as a 'green' insulation material in building retrofit projects [143] because of its relatively low cost and high  $R$ -value compared with other insulation materials.

In this study, sprayed polyurethane is chosen to be installed on the building's envelope. According to the experiments on the thermal performance of insulation materials, which are conducted by the Army Engineer Research and Development Center (ERDC) in US, the performance of sprayed polyurethane keeps decreasing over time. The attenuation function of its  $R$ -value can be fitted to an exponential formulation by [144]

$$R_p(t) = \begin{cases} e^{-\left(\frac{t}{28}\right)^{0.5}}, & t > 0, \\ 0, & t \leq 0, \end{cases} \quad (5.1)$$

in which  $R_p(t)$  is the  $R$ -value of sprayed polyurethane in year  $t$ . When the  $R$ -value degrades to a very poor level, for instance, 60% of its initial value, maintenance of the envelope insulation system of the building is necessary to maintain the envelope with good thermal performance.

### 5.2.2 Energy consumption of the building

The energy consumed by space heating in a general building,  $E_{heat}$ , can be calculated by equations (2.7)-(2.13).

The energy consumed by space cooling in a general building,  $E_{cool}$ , can be calculated by equations (2.17)-(2.20).

The energy consumed by water heating in a general building,  $E_{water}$ , can be calculated by equation (2.21).

In this chapter, maintenance of the windows of the building is not considered during the project period. Therefore, the thermal transmission of the windows will remain unchanged after retrofit. However, the thermal transmittance of the walls and roof of the building will change owing to the insulation system installed on them and the corresponding maintenance of the system. The thermal transmittance of these two kinds of envelope components at time  $t$  can be calculated by equations (5.2)-(5.3) [118]:

$$U_{wal}(t) = \frac{1}{R_p(t) \frac{d_w}{\lambda_w} + \sum_{g=1}^G R_p(t - gT_m) \frac{d_{w,g}}{\lambda_w}}, \quad (5.2)$$

$$U_{rof}(t) = \frac{1}{R_p(t) \frac{d_r}{\lambda_r} + \sum_{g=1}^G R_p(t - gT_m) \frac{d_{r,g}}{\lambda_r}}, \quad (5.3)$$

where  $g$  is a positive integer,  $d_w$  and  $d_r$  are the thicknesses of the insulation materials added to the external walls and roof of the building during the retrofit measured in m, respectively,  $\lambda_w$  and  $\lambda_r$  are the thermal conductivities of the external wall and roof insulation materials used for the retrofit measured in W/m°C, respectively,  $d_{w,g}$  and  $d_{r,g}$  are the thicknesses of the external wall insulation material and roof insulation material that are applied to the walls and roof of the building during the  $g$ -th maintenance activity, respectively, measured in m,  $T_m$  is the maintenance interval, which means the maintenance activity for the building envelope insulation system happens every  $T_m$  years.

### 5.3 OPTIMIZATION

The purpose of this study is to find an optimal maintenance plan for the building's envelope insulation system after retrofit to improve the energy efficiency of the building to ensure the energy sustainability and financial feasibility of the building envelope retrofit and maintenance project, i.e., maximizing the total energy savings and NPV and minimizing the payback period of the project by determining the optimal thicknesses of the wall and roof insulation materials to be installed on the building during each maintenance activity. Therefore, the maintenance plan for the envelope insulation system is a multi-objective optimization problem, which can be described in the following format:

$$\begin{aligned} &\mathbf{max} \quad \text{energy savings, and NPV} \\ &\mathbf{min} \quad \text{payback period} \\ &\mathbf{s.t.} \quad \text{budget available, and thickness of insulation materials.} \end{aligned} \quad (5.4)$$

### 5.3.1 Decision variables

The maintenance actions for the insulation system installed on the building's envelope during the project period include installing insulation materials on the walls and roof of the building. The maintenance activity happens once every  $T_m$  years over the project period. Assume that  $G$  maintenance activities take place in total. Then the decision variable of the optimization problem, which represents an optimal maintenance plan, can be given by

$$X = [d_{w,1}, d_{w,2}, \dots, d_{w,G}, d_{r,1}, d_{r,2}, \dots, d_{r,G}].$$

### 5.3.2 Objectives

The objectives of the optimization problem are to maximize the energy savings and NPV, and minimize the payback period of the building envelope retrofit and maintenance project. The models used to calculate the energy and economic benefits are presented as below.

The total energy savings of the project,  $ES_{tot}$ , can be calculated by

$$ES_{tot} = E_{pre} - E_{post} = \sum_{t=1}^T ES(t), \quad (5.5)$$

where  $ES(t)$  is the energy savings of year  $t$ . It can be calculated by

$$ES(t) = \Delta E_{heat}(t) + \Delta E_{cool}(t) + \Delta E_{water}(t). \quad (5.6)$$

The NPV of the investment for the building envelope retrofit and maintenance project over the project period can be calculated by equation (5.7):

$$NPV = \sum_{t=1}^T \frac{ES(t)p(t) - C_m(t)}{(1+d)^t} - C_r, \quad (5.7)$$

in which

$$C_r = A_{win}C_{win} + A_{wal}C_{wal} + A_{rof}C_{rof}, \quad (5.8)$$

$$C_m(t) = \begin{cases} A_{wal}C_{wal} \frac{d_{w,g}}{\lambda_{w,g}} + A_{rof}C_{rof} \frac{d_{r,g}}{\lambda_{r,g}}, & t = gT_m, \\ 0, & otherwise. \end{cases} \quad (5.9)$$

In these equations,  $C_m(t)$  is the maintenance cost in year  $t$  measured in \$. When  $C_m(t) = 0$ , it indicates that no maintenance activity takes place in year  $t$ .  $C_{win}$  is the cost of new windows for retrofit measured

in  $\$/m^2$ ,  $C_{wal}$  and  $C_{rof}$  are the costs of wall insulation materials and roof insulation materials used for retrofit measured in  $\$/m^2$ , respectively.

The payback period of the building project taking the discount rate into consideration,  $T_p$ , can be calculated using equation (2.28).

The nonlinear multiple-objective optimization problem in this chapter can be converted into a single-objective optimization problem, which is described by

$$J = -w_1 ES_{tot} - w_2 NPV + w_3 T_p. \quad (5.10)$$

During the optimization process, the three terms in the objective function are standardized for the convenience of tuning the weighting factors.

### 5.3.3 Constraints

The constraints of the optimization problem in this chapter consist of two parts, including budget limit and physical limit.

The budget limit of the building envelope retrofit and maintenance project is described by

$$C_{tot} \leq \beta, \quad (5.11)$$

in which the total cost of the project,  $C_{tot}$ , can be calculated by

$$C_{tot} = A_{win}C_{win} + A_{wal}C_{wal} + A_{rof}C_{rof} + \sum_{t=1}^T C_m(t). \quad (5.12)$$

The thickness of the SPF insulation materials added to the walls and roof of the building during maintenance activities are set to values that do not exceed 0.03 m in case of causing overheating and foam scorching [145]. This constraint is described by

$$0 \leq d_{w,g}, d_{r,g} \leq 0.03 \quad \forall g \in \{1, 2, \dots, G\}. \quad (5.13)$$

## 5.4 CASE STUDY

### 5.4.1 Case information

A case study is investigated to verify the potential of maintenance optimization for the building envelope system in energy conservation. The existing building under study is a family house with two floors. The detailed structure of the building is shown in Fig. 5.1. The gross area of the building is 97 m<sup>2</sup> and the area of the windows is one tenth of it.

In the existing building, no insulation system has been installed on the walls and the roof. Moreover, the thermal performance of the windows is not good. To improve the energy efficiency of the envelope system, it is considered to apply sprayed polyurethane insulation materials to the walls and roof of the building and to replace the windows with better ones. Detailed information on the insulation materials and new windows are provided in Tables 5.1-5.2.

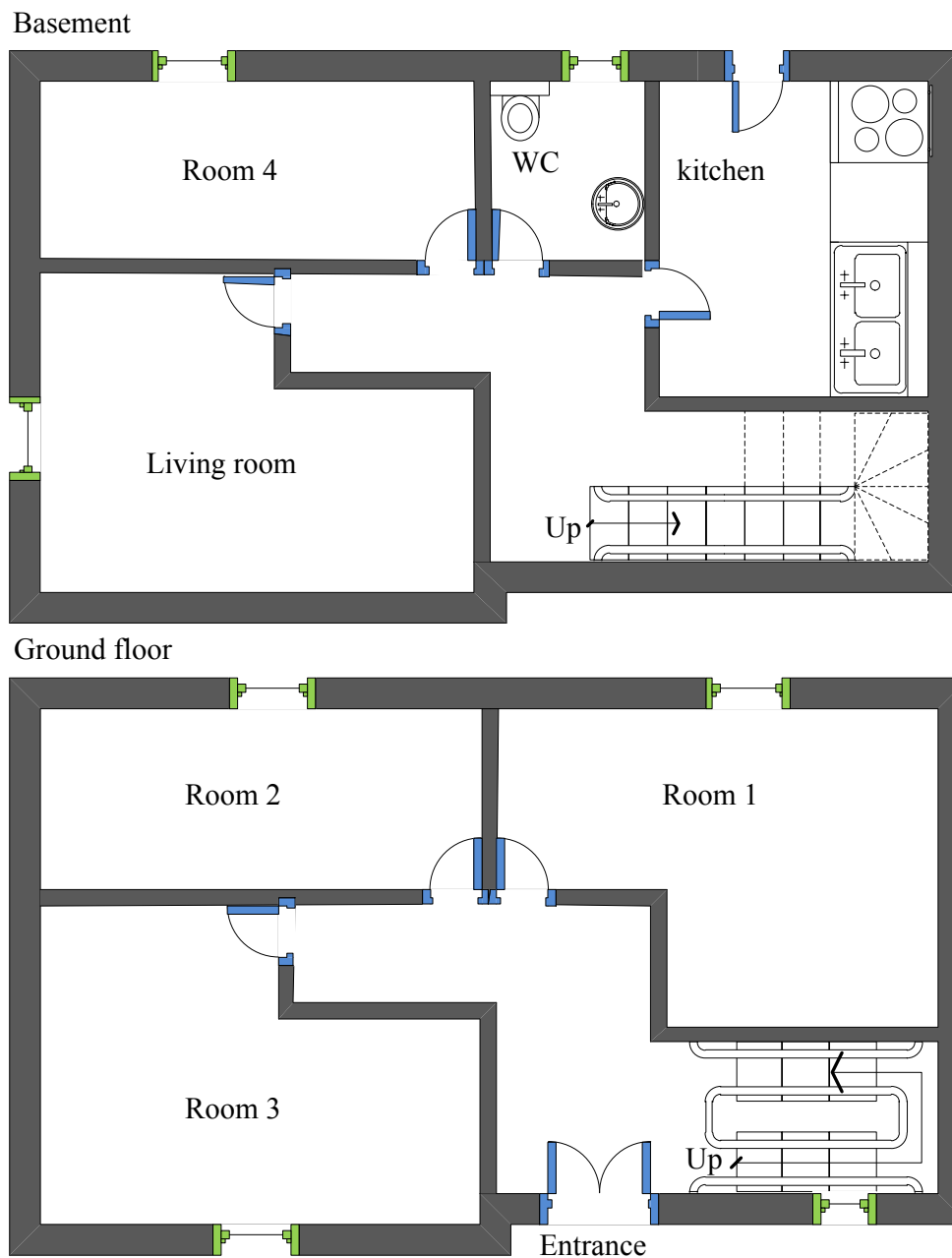
**Table 5.1.** Detailed information on sprayed polyurethane insulation materials

Category	Insulation materials	$d$ (m)	$\lambda$ (W/m <sup>2</sup> °C)	Cost (\$/m <sup>2</sup> )
Wall	Sprayed polyurethane	0.0518	0.0252	21.53
Roof	Sprayed polyurethane	0.0200	0.0420	8.23

**Table 5.2.** Detailed information on new windows

Description	$U_i$ (W/m <sup>2</sup> °C)	$\delta_i$ (%)	$C_i^{win}$ (\$/m <sup>2</sup> )
Double glazing, typical glazing	1.6	44	174.62

In view of the thermal performance degradation of the SPF insulation materials, an optimal maintenance plan for the building envelope insulation system is developed based on the proposed optimization model to ensure sustainable energy savings over the project period. As the thermal performance of SPF insulation material will degrade to a level of 60% of its initial value in six years, according to the degradation model in Section 5.2.1, the maintenance interval,  $T_m$ , is set to 6. That is to say, maintenance activities will take place every six years. During each maintenance activity, the SPF insulation materials of different thickness and thermal conductivity, which are determined by the optimization model, will be installed on the walls and roof of the building.



**Figure 5.1.** Structure of the family house under study.



**5.4.2 Results analysis**

The optimization problem is solved with the weighted sum method. During the optimization process, the values of the weighting factors for the objectives, including energy savings, NPV and the payback period, are set as  $w_1 = 0.8, w_2 = 0.6, w_3 = 0.2$  to illustrate the trade-off between them. The corresponding optimal results are provided in Table 5.3 and Fig. 5.2.

**Table 5.3.** Performance of optimized solutions with different budgets

	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6
$\beta$ (\$)	4000	5000	6000	7000	8000	9000
$C_{tot}$ (\$)	4000	5000	6000	7000	8000	9000
$ES_{tot}$ (kWh)	128749	231639	259268	276574	286476	294626
$ES_p$ (%)	17	31	34	36	38	39
NPV (\$)	11075	20857	22375	22785	22501	22010
$T_p$ (month)	44	57	78	88	97	105
$d_{w,1}$ (m)	0	0.004	0.015	0.024	0.030	0.030
$d_{w,2}$ (m)	0	0	0.001	0.007	0.009	0.027
$d_{w,3}$ (m)	0	0	0	0	0	0
$d_{r,1}$ (m)	0.002	0.030	0.030	0.030	0.030	0.030
$d_{r,2}$ (m)	0	0.010	0.026	0.030	0.030	0.030
$d_{r,3}$ (m)	0	0	0	0.001	0.030	0.025

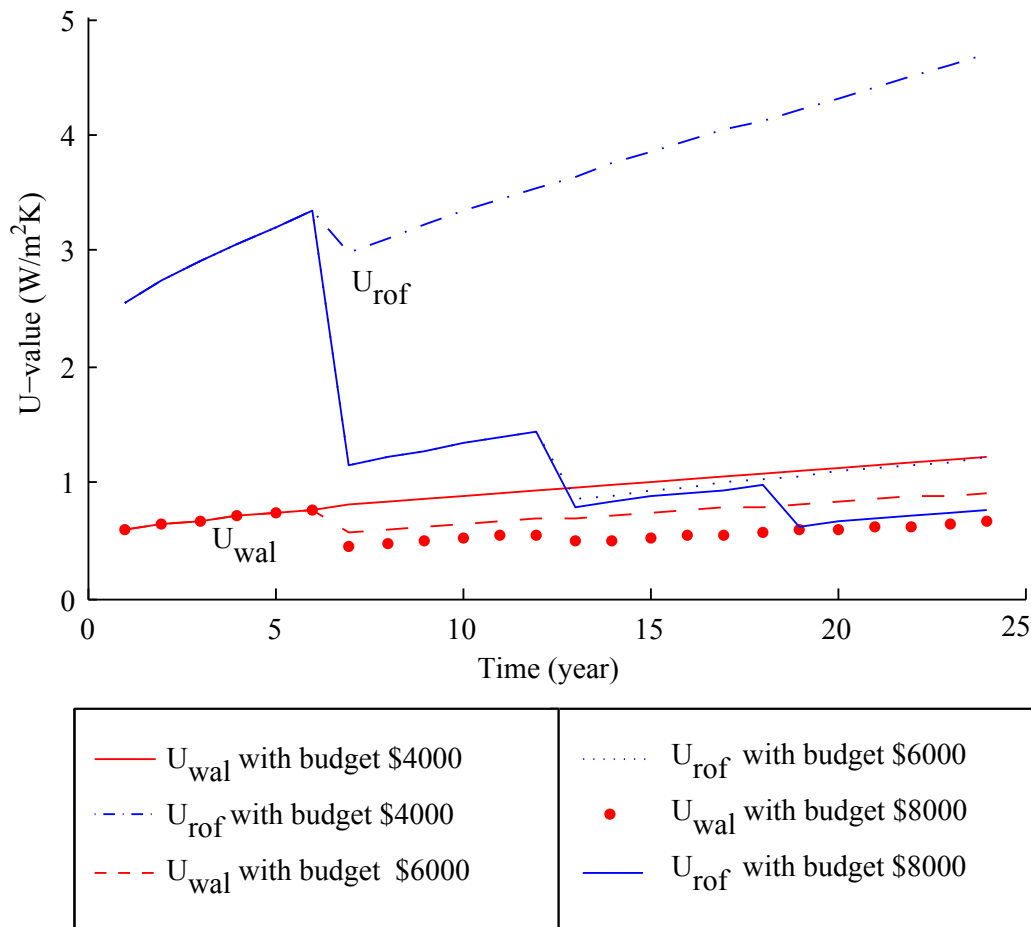
Table 5.3 provides the optimal maintenance plans for the building envelope insulation system with different budgets, as well as the resulting energy and economic benefits of these maintenance plans. The optimal maintenance actions are indicated by the numbers in the last six rows of the last six columns of the table. For instance, the fourth column gives the optimal solution obtained with the budget of \$6000, which is to install the SPF insulation materials on the walls and roof of the building at the end of years 6 and 12. The thicknesses of the SPF installed on the walls are 15 mm and 1 mm during the two maintenance activities, respectively, and those installed in the roof are 30 mm and 26 mm, respectively. The energy savings and economic indicators of the project are reflected in the table from the fourth to the seventh row. For instance, the numbers from the fourth to the seventh row in the second column mean that 128.7 MWh of energy savings and \$11075 of economic benefits of the project can be achieved with a payback period of 44 months when a budget of \$4000 is allocated.

From the table, it can be seen that NPV keeps increasing with growing investments less than \$7000, while it keeps decreasing with growing investments exceeding \$7000. The energy savings and payback period of the project keep growing with increasing investments. In particular, Table 5.3 shows that the energy savings increase more slowly with growing investments that exceed \$7000. Therefore, decision makers can determine their investments based on their interests, either increasing the investment to achieve more energy savings or decreasing the investment to shorten the payback period.

With the budget of \$4000, the investment is almost entirely spent on retrofitting the envelope components of the building and only a small part is spent on maintenance. In this case, 17% energy savings and \$11075 of economic savings are achieved, which verifies that retrofitting the envelopes of existing buildings is an effective and profitable way to improve the energy efficiency of the buildings. When the budget for the project increases from \$4000 to \$5000, some maintenance activities are done for the envelope insulation system with the extra investment, the proportion of energy savings goes up from 17% to 31% and the NPV goes up from \$11075 to \$20875. That is to say, both the energy savings and the economic benefits of the building project are almost doubled with maintenance, which fully demonstrates the importance and effectiveness of a maintenance plan for the building envelope insulation system with respect to energy conservation.

In Table 5.3, it is observed that the thickness of the SPF insulation added to the walls of the building in the second maintenance activity increases from 9 to 27 mm while that of the insulation added to the roof in the third maintenance activity decreases from 30 to 25 mm when the budget grows from \$8000 to \$9000. This demonstrates that the maintenance priority is given to the walls' insulation instead of the roof's insulation when the investment is not sufficient. The phenomenon can be explained by the reasons that the area of the walls is larger and the thermal property of the insulation materials for the walls is better compared with the situation of the roof. Therefore, the optimal maintenance plan for the building envelope insulation system does not simply entail repairing the roof first because the insulation material for it is cheaper, which verifies that the proposed optimization model is useful to find optimal maintenance plans for similar building projects. In addition, the model gives decision makers or potential investors a convenient approach to achieve the desired maintenance plans based on their preferences in terms of the objectives in the objective function by tuning the corresponding weighting factors.

Fig. 5.2 shows the thermal transmission changes of the external walls and roof of the building during



**Figure 5.2.** U-value changes of external walls and roof over the evaluation period.

the whole project period. The smaller the U-value is, the better the thermal performance. In Fig. 5.2, the red lines represent the thermal transmissions of the external walls,  $U_{wal}$ , and the blue ones represent those of the roof,  $U_{rof}$ , with various investments. It can be noted that the  $U_{wal}$  and  $U_{rof}$  keep increasing over time without maintenance, which means the energy efficiency of the building envelope system keeps getting worse. This is because the thermal performance of the envelope insulation system degrades over time. For example, the solid red line in Fig. 5.2 for the walls with a budget of \$4000 keeps going up. With the same budget, the blue solid line for the roof keeps going up; however, it decreases to a smaller value rapidly at the end of year 6 in response to the maintenance at the time. This phenomenon fully demonstrates that proper maintenance for the building envelope insulation system is helpful to ensure that the thermal performance of the envelope to remains in good condition. Fig. 5.2 shows that the U-values of the walls and roof all keep going up without maintenance and will decrease to a smaller value when maintenance is done. Therefore, the numbers of the tuning points in the lines for the walls and roof thermal transmissions are the same as the number of maintenance

activities. For instance, three maintenance activities for the roof insulation system happen in the project period, so that there are three tuning points in the line for  $U_{rof}$  with the budget of \$8000.

It is interesting to observe that the degrees of the changes in the U-values of the envelope components during each maintenance activity are different. The improvement of the thermal performances of the walls and roof in the earlier maintenance is greater than that in later maintenance. The most representative example is the lines for  $U_{wal}$  and  $U_{rof}$  with the budget of \$8000 shown in Fig. 5.2. This can be explained by the fact that the insulation of the envelope components still has some ability to prevent heat transfer between the indoor and outdoor environments in spite of thermal performance degradation before maintenance takes place again. According to the figure, one can conclude that the thermal performance of the building envelope insulation system keeps getting better with growing investments.

## 5.5 CONCLUSION

An optimization model for building envelope maintenance planning after retrofit is presented in this chapter. The purpose is to ensure that the energy efficiency of the building's envelope after retrofit to remain in good condition through maintenance, aiming at maximizing the energy savings and NPV as well as minimizing the payback period of the project. During the retrofit process, the windows are replaced with better ones and the walls and roof are fitted with insulation materials to improve the energy efficiency of the building's envelope system. After the retrofit, maintenance of the envelope insulation system takes place at fixed time intervals to ensure the sustainability of energy savings of the building project. During the modeling process, the performance degradation of insulation materials is taken into consideration in order to estimate the energy and financial benefits of the building project accurately. The economic benefits, the NPV and payback period, which are important indicators for decision makers or potential investors to evaluate investments, are taken into consideration. The results of a case study demonstrate the effectiveness and feasibility of the proposed optimization model for improving the energy efficiency of existing buildings by retrofitting the envelope system and maintaining it.

## **CHAPTER 6 CONCLUSION AND FUTURE WORK**

This thesis focuses on problems related to green retrofit and maintenance planning for existing buildings, aiming at improving their energy efficiency and ensuring that they comply with the green building policy implemented in South Africa. In this section, the main contributions and conclusions of this thesis are summarized, followed by a brief look into potential future work in this research area.

### **6.1 CONCLUSION**

Approaches to green retrofit and maintenance planning for existing buildings have been proposed in this thesis from Chapter 2 to Chapter 5. The following conclusions are drawn based on the models and case studies presented in those chapters.

Firstly, an optimization model for building envelope retrofit planning is introduced in Chapter 2 to fill the gap in the literature regarding optimal retrofit planning for building envelopes. The model maximizes the energy savings and the benefits of occupants and investors by improving the energy efficiency of existing buildings with a given budget. In the modeling process, the performance degradation of the rooftop PV system that was installed and the corresponding maintenance for it are taken into account in estimating the energy savings and economic benefits of the retrofit project accurately. Factors such as NPV and the payback period, which indicate the profitability of an investment, are built into the model to help decision makers to make informed decisions. It can be concluded from this part of the study that retrofitting the envelope system of a building with energy-efficient interventions is a feasible and effective way to reduce the energy demand of the building in a reasonably cost-effective manner.

Secondly, an optimization model dealing with the systematic retrofit of both the envelope and indoor appliances of a building is developed in Chapter 3, taking into account the compliance with the green building policy in South Africa. This model contributes to the body of knowledge in the field of green building retrofit in two respects. It is the first study that considers both the envelope and the indoor systems of a building at the same time in the retrofit planning phase. Moreover, it is also the first study dealing with South African green building policy compliance in the retrofit plan. The optimal retrofit plan presented helps the investment decision makers to select the best retrofit activities on a yearly basis to ensure that the energy performance of the building is improved and the resulting building complies with the green building policy. In this way, the greatest energy savings are obtained, with a reasonable payback period for the investment. A case study validated the effectiveness and confirmed the importance of the model for decision makers, as intuitive plans will lead to non-optimal retrofit. It was also concluded that the South African tax incentive program on energy savings interventions has little impact on the building energy efficiency retrofit project in terms of its financial feasibility. It was concluded from this chapter that the resulting optimization problem to determine the retrofit plan, including both the envelope and indoor systems, is quite complex and difficult to solve.

Thirdly, two methods to simplify the systematic retrofit optimization problem presented in Chapter 3 and the detailed audit involved are proposed in Chapter 4, taking advantage of grouping theory and ‘notch test’ data on the energy savings of retrofitting a certain item in a homogeneous group. These methods are shown to be able to reduce the complexity of solving the optimization problem effectively and the detail level of the energy audit required. Each of the two methods features a different level of details on the retrofit plan and can be used depending on the preferences of decision makers.

Finally, an optimization model for building envelope maintenance planning after retrofit is presented in Chapter 5 in view of lack of such studies in the literature and the fact that the thermal performance of the envelope components inevitably deteriorate over time. Therefore, the model is proposed to find cost-effective maintenance plans for the envelope system after retrofit to ensure that sustainable energy savings from the envelope retrofit can be achieved. The results of a case study validate the usefulness of this maintenance optimization model.

## 6.2 FUTURE WORK

Potential improvements on the research presented in this dissertation could be achieved through the following:

- 1) The study reported in this thesis presents a general framework for green building retrofit. The case studies are based on building and energy data that are available either in the public domain or to the Center of New Energy Systems at the University of Pretoria. The research can be further improved in terms of accuracy if more data can be obtained and used to improve the accuracy of the model.
- 2) There is a lack of performance degradation models for the items and subsystems involved in this thesis. Only a few such models can be found in the literature. The proposed model can be further polished if better performance degradation models of such systems are developed.
- 3) This thesis investigates the optimal retrofit plans or optimal maintenance plans separately. In future work, a systematic approach to optimize both the retrofit and maintenance plan simultaneously should be studied to improve the methods presented in this thesis further.
- 4) It is foreseeable that the optimization model required will be more complex and difficult to solve if more systems are considered and the retrofit and maintenance plans are considered together. Therefore, efficient algorithms specially designed to solve the building retrofit and maintenance planning problems will be a welcome topic and valid future research topic.

## REFERENCES

- [1] H. Khatib, "IEA world energy outlook 2011: A comment," *Energy Policy*, vol. 48, pp. 737 – 743, 2012.
- [2] J. Woo and C. Menassa, "Virtual retrofit model for aging commercial buildings in a smart grid environment," *Energy and Buildings*, vol. 80, pp. 424 – 435, 2014.
- [3] Z. Ma, P. Cooper, D. Daly, and L. Ledo, "Existing building retrofits: Methodology and state-of-the-art," *Energy and Buildings*, vol. 55, pp. 889 – 902, 2012.
- [4] B. Wang, X. Xia, and J. Zhang, "A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings," *Energy and Buildings*, vol. 77, pp. 227 – 235, 2014.
- [5] Architecture 2030, "Roadmap to zero emissions," Report, 2014, submission to the Ad Hoc working group on the Durban platform for enhanced action.
- [6] World Green Building Council, "Annual report 2015/2016," Report, 2016.
- [7] *Energy performance certificates for buildings*, 1st ed., South African Bureau of Standards, 2014, SANS 1544.
- [8] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galván, R. C. PortilloGuisado, M. M. Prats, J. I. León, and N. Moreno-Alfonso, "Power-electronic systems for the grid integration



- of renewable energy sources: A survey,” *IEEE Transactions on industrial electronics*, vol. 53, no. 4, pp. 1002–1016, 2006.
- [9] “ASHRAE handbook-fundamentals,” American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Tech. Rep., 2009, Atlanta GA, USA.
- [10] N. Panwar, S. Kaushik, and S. Kothari, “Role of renewable energy sources in environmental protection: A review,” *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3, pp. 1513–1524, 2011.
- [11] J. Schiffer, D. Zonetti, R. Ortega, A. M. Stanković, T. Sezi, and J. Raisch, “A survey on modeling of microgrids – from fundamental physics to phasors and voltage sources,” *Automatica*, vol. 74, pp. 135–150, 2016.
- [12] I. Ali, “Communication design for energy management automation in microgrid,” *IEEE Transactions on Smart Grid*, 2016.
- [13] W. A. Friess, K. Rakhshan, and M. P. Davis, “A global survey of adverse energetic effects of increased wall insulation in office buildings: degree day and climate zone indicators,” *Energy Efficiency*, vol. 10, no. 1, pp. 97–116, 2017.
- [14] B. Wang, “A control system framework for building energy retrofitting and maintenance planning,” Ph.D. dissertation, University of Pretoria, July 2017.
- [15] A. Von Meier, *Electric power systems: a conceptual introduction*. John Wiley & Sons, 2006.
- [16] D. Xie, Z. Xu, L. Yang, J. Østergaard, Y. Xue, and K. P. Wong, “A comprehensive LVRT control strategy for DFIG wind turbines with enhanced reactive power support,” *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 3302–3310, 2013.
- [17] X. Fang, F. Li, Y. Wei, R. Azim, and Y. Xu, “Reactive power planning under high penetration of wind energy using benders decomposition,” *IET Generation, Transmission & Distribution*, vol. 9, no. 14, pp. 1835–1844, 2015.

- [18] J. Aho, A. Buckspan, J. Laks, P. Fleming, Y. Jeong, F. Dunne, M. Churchfield, L. Pao, and K. Johnson, "A tutorial of wind turbine control for supporting grid frequency through active power control," in *American Control Conference (ACC), 2012*. IEEE, 2012, pp. 3120–3131.
- [19] J. Pahasa and I. Ngamroo, "Coordinated control of wind turbine blade pitch angle and phevs using mpcs for load frequency control of microgrid," *IEEE Systems Journal*, vol. 10, no. 1, pp. 97–105, 2016.
- [20] J. J. Justo, F. Mwasilu, and J.-W. Jung, "Doubly-fed induction generator based wind turbines: A comprehensive review of fault ride-through strategies," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 447–467, 2015.
- [21] A. Al Nabulsi and R. Dhaouadi, "Efficiency optimization of a DSP-based standalone PV system using fuzzy logic and dual-MPPT control," *IEEE Transactions on Industrial Informatics*, vol. 8, no. 3, pp. 573–584, 2012.
- [22] B. Xiao, L. Hang, J. Mei, C. Riley, L. M. Tolbert, and B. Ozpineci, "Modular cascaded H-bridge multilevel PV inverter with distributed MPPT for grid-connected applications," *IEEE Transactions on Industry Applications*, vol. 51, no. 2, pp. 1722–1731, 2015.
- [23] C. R. Sullivan, J. J. Awerbuch, and A. M. Latham, "Decrease in photovoltaic power output from ripple: Simple general calculation and the effect of partial shading," *IEEE Transactions on Power Electronics*, vol. 28, no. 2, pp. 740–747, 2013.
- [24] Y. Shi, R. Li, Y. Xue, and H. Li, "High-frequency-link-based grid-tied PV system with small DC-link capacitor and low-frequency ripple-free maximum power point tracking," *IEEE Transactions on Power Electronics*, vol. 31, no. 1, pp. 328–339, 2016.
- [25] K. M. Abo-Al-Ez, A. Elaiw, and X. Xia, "A dual-loop model predictive voltage control/sliding-mode current control for voltage source inverter operation in smart microgrids," *Electric Power Components and Systems*, vol. 42, no. 3-4, pp. 348–360, 2014.
- [26] Y. Liu, Q. Zhang, C. Wang, and N. Wang, "A control strategy for microgrid inverters based

- on adaptive three-order sliding mode and optimized droop controls,” *Electric Power Systems Research*, vol. 117, pp. 192–201, 2014.
- [27] D. G. Wilson, R. D. Robinett, W. W. Weaver, R. H. Byrne, and J. Young, “Nonlinear power flow control design of high penetration renewable sources for ac inverter based microgrids,” in *2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*. IEEE, 2016, pp. 701–708.
- [28] H. Wu, K. Sun, L. Chen, L. Zhu, and Y. Xing, “High step-up/step-down soft-switching bidirectional dc–dc converter with coupled-inductor and voltage matching control for energy storage systems,” *IEEE Transactions on Industrial Electronics*, vol. 63, no. 5, pp. 2892–2903, 2016.
- [29] Y.-F. Wang, L.-K. Xue, C.-S. Wang, P. Wang, and W. Li, “Interleaved high-conversion-ratio bidirectional dc–dc converter for distributed energy-storage systems – circuit generation, analysis, and design,” *IEEE Transactions on Power Electronics*, vol. 31, no. 8, pp. 5547–5561, 2016.
- [30] D. Zhang and X. Xia, “Distributed illumination control of led networked systems via local occupancy information.” The 56th IEEE Conference on Decision and Control, Melbourne, Australia, 12-15 December, 12-15 December 2017.
- [31] J. Mei and X. Xia, “Energy-efficient predictive control of indoor thermal comfort and air quality in a direct expansion air conditioning system,” *Applied Energy*, vol. 195, pp. 439–452, 2017.
- [32] D. Setlhaolo, X. Xia, and J. Zhang, “Optimal scheduling of household appliances for demand response,” *Electric Power Systems Research*, vol. 116, pp. 24–28, 2014.
- [33] D. Setlhaolo and X. Xia, “Optimal scheduling of household appliances with a battery storage system and coordination,” *Energy and Buildings*, vol. 94, pp. 61–70, 2015.
- [34] D. Setlhaolo and X. Xia, “Combined residential demand side management strategies with coordination and economic analysis,” *International Journal of Electrical Power & Energy Systems*, vol. 79, pp. 150–160, 2016.

- [35] F. Yang and X. Xia, "Techno-economic and environmental optimization of a household photovoltaic-battery hybrid power system within demand side management," *Renewable Energy*, vol. 108, pp. 132–143, 2017.
- [36] F. Shrouf, J. Ordieres-Meré, A. García-Sánchez, and M. Ortega-Mier, "Optimizing the production scheduling of a single machine to minimize total energy consumption costs," *Journal of Cleaner Production*, vol. 67, pp. 197–207, 2014.
- [37] R. Sen and S. C. Bhattacharyya, "Off-grid electricity generation with renewable energy technologies in india: An application of homer," *Renewable Energy*, vol. 62, pp. 388–398, 2014.
- [38] A. Papavasiliou and S. S. Oren, "Large-scale integration of deferrable demand and renewable energy sources," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 489–499, 2014.
- [39] H. Tazvinga, X. Xia, and J. Zhang, "Minimum cost solution of photovoltaic–diesel–battery hybrid power systems for remote consumers," *Solar Energy*, vol. 96, pp. 292–299, 2013.
- [40] H. Tazvinga, B. Zhu, and X. Xia, "Energy dispatch strategy for a photovoltaic–wind–diesel–battery hybrid power system," *Solar Energy*, vol. 108, pp. 412–420, 2014.
- [41] H. Tazvinga, B. Zhu, and X. Xia, "Optimal power flow management for distributed energy resources with batteries," *Energy Conversion and Management*, vol. 102, pp. 104–110, 2015.
- [42] E. Asadi, M. G. da Silva, C. H. Antunes, and L. Dias, "Multi-objective optimization for building retrofit strategies: A model and an application," *Energy and Buildings*, vol. 44, pp. 81 – 87, 2012.
- [43] C. Diakaki, E. Grigoroudis, N. Kabelis, D. Kolokotsa, K. Kalaitzakis, and G. Stavrakakis, "A multi-objective decision model for the improvement of energy efficiency in buildings," *Energy*, vol. 35, no. 12, pp. 5483 – 5496, 2010.
- [44] J. Zuo and Z.-Y. Zhao, "Green building research–current status and future agenda: A review," *Renewable and Sustainable Energy Reviews*, vol. 30, pp. 271–281, 2014.

- [45] P. Wu, C. Mao, J. Wang, Y. Song, and X. Wang, "A decade review of the credits obtained by leed v2. 2 certified green building projects," *Building and Environment*, vol. 102, pp. 167–178, 2016.
- [46] "International performance measurement and verification protocol (IPMVP)," Efficiency Valuation Organization (EVO), Tech. Rep., 1997.
- [47] L. Kang and Y. Liu, "Multi-objective optimization on a heat exchanger network retrofit with a heat pump and analysis of CO<sub>2</sub> emissions control," *Applied Energy*, vol. 154, pp. 696 – 708, 2015.
- [48] Y. Sun, P. Huang, and G. Huang, "A multi-criteria system design optimization for net zero energy buildings under uncertainties," *Energy and Buildings*, vol. 97, pp. 196 – 204, 2015.
- [49] Y. Shao, P. Geyer, and W. Lang, "Integrating requirement analysis and multi-objective optimization for office building energy retrofit strategies," *Energy and Buildings*, vol. 82, pp. 356 – 368, 2014.
- [50] E. Antipova, D. Boer, G. Guillén-Gosálbez, L. F. Cabeza, and L. Jiménez, "Multi-objective optimization coupled with life cycle assessment for retrofitting buildings," *Energy and Buildings*, vol. 82, 2014.
- [51] B. Wang, Z. Wu, B. Zhu, and X. Xia, "Optimal control of maintenance instants and intensities in building energy efficiency retrofitting project," *The 54th IEEE Conference on Decision and Control*, Osaka, Japan, 15-18 December, 2015.
- [52] B. Wang and X. Xia, "Optimal maintenance planning for building energy efficiency retrofitting from optimization and control system perspectives," *Energy and Buildings*, vol. 96, pp. 299 – 308, 2015.
- [53] C. Becchio, S. Corgnati, E. Fabrizio, V. Monetti, and F. Seguro, "Application of the LEED PRM to an Italian existing building," *Energy Procedia*, vol. 62, pp. 141 – 149, 2014.

- [54] D. Castro-Lacouture, J. A. Sefair, L. Flórez, and L. Andrés, "Optimization model for the selection of materials using a LEED-based green building rating system in Colombia," *Building and Environment*, vol. 44, no. 6, pp. 1162 – 1170, 2009.
- [55] P. Boarin, D. Guglielmino, A. L. Pisello, and F. Cotana, "Sustainability assessment of historic buildings: Lesson learnt from an Italian case study through LEED rating," *Energy Procedia*, vol. 61, pp. 1029–1032, 2014.
- [56] M. Michael, L. Zhang, and X. Xia, "An optimal model for a building retrofit with LEED standard as reference protocol," *Energy and Buildings*, vol. 139, pp. 22 – 30, 2017.
- [57] E. Bertone, O. Sahin, R. A. Stewart, P. Zou, M. Alam, and E. Blair, "State-of-the-art review revealing a roadmap for public building water and energy efficiency retrofit projects," *International Journal of Sustainable Built Environment*, vol. 5, no. 2, pp. 526–548, 2016.
- [58] A. Pinto, A. S. Afonso, A. S. Santos, C. Pimentel-Rodrigues, and F. Rodrigues, "Nexus water energy for hotel sector efficiency," *Energy Procedia*, vol. 111, pp. 215 – 225, 2017.
- [59] S. Becken and C. Lee McLennan, "Evidence of the water-energy nexus in tourist accommodation," *Journal of Cleaner Production*, vol. 144, pp. 415 – 425, 2017.
- [60] E. M. Wanjiru and X. Xia, "Energy-water optimization model incorporating rooftop water harvesting for lawn irrigation," *Applied Energy*, vol. 160, pp. 521 – 531, 2015.
- [61] E. M. Wanjiru, L. Zhang, and X. Xia, "Model predictive control strategy of energy-water management in urban households," *Applied Energy*, vol. 179, pp. 821 – 831, 2016.
- [62] K. Gatt and C. Schranz, "Retrofitting a 3 star hotel as a basis for piloting water minimisation interventions in the hospitality sector," *International Journal of Hospitality Management*, vol. 50, pp. 115 – 121, 2015.
- [63] B. Wang and X. Xia, "A multistate-based control system approach toward optimal maintenance planning," *IEEE Transactions on Control Systems Technology*, vol. 25, 2017.

- [64] Y. Huang, J. Niu, and T. Chung, "Study on performance of energy-efficient retrofitting measures on commercial building external walls in cooling-dominant cities," *Applied Energy*, vol. 103, pp. 97 – 108, 2013.
- [65] J. Yu, L. Tian, X. Xu, and J. Wang, "Evaluation on energy and thermal performance for office building envelope in different climate zones of China," *Energy and Buildings*, vol. 86, pp. 626 – 639, 2015.
- [66] M. Carlini, E. Allegrini, D. Zilli, and S. Castellucci, "Simulating heat transfers through the building envelope: A useful tool in the economical assessment," *Energy Procedia*, vol. 45, pp. 395 – 404, 2014.
- [67] H. U. Rehman, "Experimental performance evaluation of solid concrete and dry insulation materials for passive buildings in hot and humid climatic conditions," *Applied Energy*, vol. 185, pp. 1585 – 1594, 2017.
- [68] Z. Zhou, L. Feng, S. Zhang, C. Wang, G. Chen, T. Du, Y. Li, and J. Zuo, "The operational performance of "net zero energy building": A study in China," *Applied Energy*, vol. 177, pp. 716 – 728, 2016.
- [69] C. Koo, S. Park, T. Hong, and H. S. Park, "An estimation model for the heating and cooling demand of a residential building with a different envelope design using the finite element method," *Applied Energy*, vol. 115, pp. 205 – 215, 2014.
- [70] T. M. Echenagucia, A. Capozzoli, Y. Cascone, and M. Sassone, "The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis," *Applied Energy*, vol. 154, pp. 577 – 591, 2015.
- [71] X. Sang, W. Pan, and M. Kumaraswamy, "Informing energy-efficient building envelope design decisions for Hong Kong," *Energy Procedia*, vol. 62, pp. 123 – 131, 2014.
- [72] A. Bastani, F. Haghghat, and J. Kozinski, "Designing building envelope with PCM wallboards: Design tool development," *Renewable and Sustainable Energy Reviews*, vol. 31, pp. 554 – 562,

- 2014.
- [73] M. Karimpour, M. Belusko, K. Xing, J. Boland, and F. Bruno, "Impact of climate change on the design of energy efficient residential building envelopes," *Energy and Buildings*, vol. 87, pp. 142 – 154, 2015.
- [74] G. M. Revel, M. Martarelli, M. Emiliani, L. Celotti, R. Nadalini, A. D. Ferrari, S. Hermanns, and E. Beckers, "Cool products for building envelope - Part II: Experimental and numerical evaluation of thermal performances," *Solar Energy*, vol. 105, pp. 780 – 791, 2014.
- [75] J. Koci, J. Madera, M. Jerman, and R. Cerny, "Computational assessment of thermal performance of contemporary ceramic blocks with complex internal geometry in building envelopes," *Energy and Buildings*, vol. 99, pp. 61 – 66, 2015.
- [76] T. Zhang, Y. Tan, H. Yang, and X. Zhang, "The application of air layers in building envelopes: A review," *Applied Energy*, vol. 165, pp. 707 – 734, 2016.
- [77] R. Urquhart, R. Richman, and G. Finch, "The effect of an enclosure retrofit on air leakage rates for a multi-unit residential case-study building," *Energy and Buildings*, vol. 86, pp. 35–44, 2015.
- [78] D. A. Chwieduk, "Some aspects of energy efficient building envelope in high latitude countries," *Energy Procedia*, vol. 57, pp. 1898 – 1907, 2014.
- [79] P. Lie, N. Zhu, D. Li, J. Shen, and X. Cui, "Determination of the insulation thickness for the residential building envelope in severe cold areas," in *the 2nd International Conference on Consumer Electronics, Communications and Networks*, Yichang, China, 21-23 April 2012, pp. 992–996.
- [80] D. Gossard, B. Lartigue, and F. Thellier, "Multi-objective optimization of a building envelope for thermal performance using genetic algorithms and artificial neural network," *Energy and Buildings*, vol. 67, pp. 253 – 260, 2013.



- [81] G. Nair, L. Gustavsson, and K. Mahapatra, "Owners perception on the adoption of building envelope energy efficiency measures in Swedish detached houses," *Applied Energy*, vol. 87, no. 7, pp. 2411 – 2419, 2010.
- [82] Y. Fan and X. Xia, "A multi-objective optimization model for energy-efficiency building envelope retrofitting plan with rooftop PV system installation and maintenance," *Applied Energy*, vol. 189, pp. 327 – 335, 2017.
- [83] Y. Fan and X. Xia, "An optimal maintenance plan for building envelope insulation materials after retrofitting," in *2015 Chinese Automation Congress*, Wuhan, China, 27-29 November 2015.
- [84] "LEED leadership in energy and environmental design for existing buildings," 2012, accessed: June 2015. [Online]. Available: <http://new.usgbc.org/leed>
- [85] P. O. Akadiri, P. O. Olomolaiye, and E. A. Chinyio, "Multi-criteria evaluation model for the selection of sustainable materials for building projects," *Automation in Construction*, vol. 30, no. 0, pp. 113 – 125, 2013.
- [86] E. K. Z. Arturas Kaklauskas and S. Raslanas, "Multivariant design and multiple criteria analysis of building refurbishments," *Energy and Buildings*, vol. 37, no. 4, pp. 361 – 372, 2005.
- [87] M. Salminen, M. Palonen, and K. Sirén, "Combined energy simulation and multi-criteria optimisation of a LEED-certified building," in *Proceedings of the building simulation and optimization conference*, Leicestershire, England, 11-12 Sep. 2012.
- [88] D. S. Remer and A. P. Nieto, "A compendium and comparison of 25 project evaluation techniques. Part 1: Net present value and rate of return methods," *International Journal of Production Economics*, vol. 42, no. 1, pp. 79 – 96, 1995.
- [89] F. Kreith and D. Y. Goswami, Eds., *Energy Management and Conservation Handbook*. CCC Press, 2007.

- [90] E. M. Malatji, J. Zhang, and X. Xia, "A multiple objective optimisation model for building energy efficiency investment decision," *Energy and Buildings*, vol. 61, pp. 81–87, 2013.
- [91] Z. Wu, X. Xia, and B. Wang, "Improving building energy efficiency by multiobjective neighborhood field optimization," *Energy and Buildings*, vol. 87, pp. 45 – 56, 2015.
- [92] K. Deb and D. Kalyanmoy, *Multi-Objective Optimization Using Evolutionary Algorithms*, New York, NY, USA, 2001.
- [93] M. C. Grillo, "Life cycle thinking: Strategies for sustainable renovation of existing buildings," Ph.D. dissertation, 2014.
- [94] "Windows and building envelope research and development: roadmap for emerging technologies," U.S. Department of Energy, Tech. Rep., 2014.
- [95] Y. Fan and X. Xia, "A multi-objective optimization model for building envelope retrofit planning." Abu Dhabi, UAE: 7th International Conference on Applied Energy, 28-31 March 2015.
- [96] X. Mao, H. Lu, and Q. Li, "A comparison study of mainstream sustainable/green building rating tools in the world," pp. 1–5, 2009.
- [97] L. E. Mavromatidis, A. Bykalyuk, and H. Lequaya, "Development of polynomial regression models for composite dynamic envelopes' thermal performance forecasting," *Applied Energy*, vol. 104, pp. 379 – 391, 2013.
- [98] Z. Wu, B. Wang, and X. Xia, "Large-scale building energy efficiency retrofit: Concept, model and control," *Energy*, vol. 109, pp. 456 – 465, 2016.
- [99] A. H. Mondal and D. Klein, "Impacts of solar home systems on social development in rural Bangladesh," *Energy for Sustainable Development*, vol. 15, no. 1, pp. 17 – 20, 2011.
- [100] E. Martinot, A. Cabraal, and S. Mathur, "World Bank/GEF solar home system projects: experiences and lessons learned 1993-2000," *Renewable and Sustainable Energy Reviews*, vol. 5,

- no. 1, pp. 39 – 57, 2001.
- [101] A. Ndiaye, A. Charki, A. Kobi, C. M. Kébé, P. A. Ndiaye, and V. Sambou, “Degradations of silicon photovoltaic modules: A literature review,” *Solar Energy*, vol. 96, pp. 140 – 151, 2013.
- [102] E. D. Dunlop, “Lifetime performance of crystalline silicon PV modules,” in *Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion*, vol. 3, Osaka, Japan, 11-18 May 2003, pp. 2927–2930 Vol.3.
- [103] D. C. Jordan and S. R. Kurtz, “Photovoltaic degradation rates – an analytical review,” *Progress in Photovoltaics: Research and Applications*, vol. 21, no. 1, pp. 12–29, 2013.
- [104] X. Ye, X. Xia, L. Zhang, and B. Zhu, “Optimal maintenance planning for sustainable energy efficiency lighting retrofit projects by a control system approach,” *Control Engineering Practice*, vol. 37, pp. 1 – 10, 2015.
- [105] R. Evins, “A review of computational optimisation methods applied to sustainable building design,” *Renewable and Sustainable Energy Reviews*, vol. 22, pp. 230 – 245, 2013.
- [106] A. Shirazi, B. Najafi, M. Aminyavari, F. Rinaldi, and R. A. Taylor, “Thermal-economic-environmental analysis and multi-objective optimization of an ice thermal energy storage system for gas turbine cycle inlet air cooling,” *Energy*, vol. 69, pp. 212 – 226, 2014.
- [107] B. Najafi, A. Shirazi, M. Aminyavari, F. Rinaldi, and R. A. Taylor, “Exergetic, economic and environmental analyses and multi-objective optimization of an sofc-gas turbine hybrid cycle coupled with an MSF desalination system,” *Desalination*, vol. 334, no. 1, pp. 46 – 59, 2014.
- [108] I. Kim and O. de Weck, “Adaptive weighted sum method for multiobjective optimization: a new method for Pareto front generation,” *Structural and Multidisciplinary Optimization*, vol. 31, no. 2, pp. 105–116, 2006.
- [109] R. T. Marler and J. S. Arora, “The weighted sum method for multi-objective optimization: new insights,” *Structural and Multidisciplinary Optimization*, vol. 41, no. 6, pp. 853–862, 2010.

## REFERENCES

---

- [110] B. Surekha, L. K. Kaushik, A. K. Panduy, P. R. Vundavilli, and M. B. Parappagoudar, "Multi-objective optimization of green sand mould system using evolutionary algorithms," *The International Journal of Advanced Manufacturing Technology*, vol. 58, no. 1, pp. 9–17, 2012.
- [111] C. Diakaki, E. Grigoroudis, and D. Kolokotsa, "Towards a multi-objective optimization approach for improving energy efficiency in buildings," *Energy and Buildings*, vol. 40, no. 9, pp. 1747 – 1754, 2008.
- [112] M. Vázquez and I. Rey-Stolle, "Photovoltaic module reliability model based on field degradation studies," *Progress in Photovoltaics: Research and Applications*, vol. 16, no. 5, pp. 419–433, 2008.
- [113] B. Marion and J. Adelstein, "Long-term performance of the SERF PV systems," in *Proceedings of the NCPV and Solar Programme Review Meeting*, Denver, Colorado, 24-26 March 2003.
- [114] R. Laronde, A. Charki, and D. Bigaud, "Lifetime estimation of a photovoltaic module based on temperature measurement," in *11 International Symposium Metrological Infrastructure*, Croatia, June 2011.
- [115] Z. Wu, H. Tazvinga, and X. Xia, "Demand side management of photovoltaic-battery hybrid system," *Applied Energy*, vol. 148, pp. 294 – 304, 2015.
- [116] B. Zhu, H. Tazvinga, and X. Xia, "Switched model predictive control for energy dispatching of a photovoltaic-diesel-battery hybrid power system," *IEEE Transactions on Control Systems Technology*, vol. 23, no. 3, pp. 1229–1236, 2015.
- [117] P. Silva, M. Almeida, L. Braganca, and V. Mesquita, "Methodology to enhance the Portuguese thermal regulation accuracy for existing buildings," in *11th International IBPSA Conference*, Glasgow, Scotland, 27-30 July 2009, pp. 576–583.
- [118] B. M. Suleiman, "Estimation of U-value of traditional North African houses," *Applied Thermal Engineering*, vol. 31, no. 11-12, pp. 1923 – 1928, 2011.

- [119] N. Wang, J. Zhang, and X. Xia, "Energy consumption of air conditioners at different temperature set points," *Energy and Buildings*, vol. 65, pp. 412–418, 2013.
- [120] S. S. Rao, *Engineering Optimization: Theory and Practice*, 4th ed. Wiley, 2009.
- [121] T. Weise, *Global Optimization Algorithm—Theory and Application*, 2nd ed., 2009.
- [122] X. Yang, Ed., *Nature-Inspired Computation in Engineering*, 1st ed. Switzerland: Springer, 2016.
- [123] A. Akhelas, K. Shahbaz, and M. Asjad, "Review of modern optimization techniques," *International Journal of Engineering Research & Technology*, vol. 4, no. 04, pp. 984–988, 2015.
- [124] E. S. M. E. H. Gamal Abd El Nasser A. Said, Abeer M. Mahmoud, "A comparative study of meta-heuristic algorithms for solving quadratic assignment problem," *International Journal of Advanced Computer Science and Applications*, vol. 5, no. 1, pp. 1–6, 2014.
- [125] K. Deep, K. P. Singh, M. L. Kansal, and C. Mohan, "A real coded genetic algorithm for solving integer and mixed integer optimization problems," *Applied Mathematics and Computation*, vol. 212, no. 2, pp. 505–518, 2009.
- [126] T. Yokota, M. Gen, and Y. Li, "Genetic algorithm for non-linear mixed integer programming problems and its applications," *Computers & Industrial Engineering*, vol. 30, no. 4, pp. 905–917, 1996.
- [127] J. Perez and J. Basterrechea, "Comparison of different heuristic optimization methods for near-field antenna measurements," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 3, pp. 549–555, 2007.
- [128] D. Whitley, "A genetic algorithm tutorial," *Statistics and Computing*, vol. 4, no. 2, pp. 65–85, 1994.

- [129] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE Transactions on Evolutionary Computation*, vol. 6, no. 2, pp. 182–197, 2002.
- [130] *The application of the National Building Regulations Part XA: Energy usage in buildings*, 1st ed., South African Bureau of Standards, 2011, SANS 10400-XA.
- [131] "ANSI/AHRI 210/240: Performance rating of unitary air-conditioning & air-source heat pump equipment," Air Conditioning, Heating and Refrigeration Institute, Tech. Rep., 2008.
- [132] X. Ye and X. Xia, "Optimal metering plan for measurement and verification on a lighting case study," *Energy*, vol. 95, pp. 580 – 592, 2016.
- [133] A. Kumar and B. Suman, "Experimental evaluation of insulation materials for walls and roofs and their impact on indoor thermal comfort under composite climate," *Building and Environment*, vol. 59, pp. 635 – 643, 2013.
- [134] M. S. Al-Homoud, "Performance characteristics and practical applications of common building thermal insulation materials," *Building and Environment*, vol. 40, no. 3, pp. 353 – 366, 2005.
- [135] I. Mandilaras, I. Atsonios, G. Zannis, and M. Founti, "Thermal performance of a building envelope incorporating ETICS with vacuum insulation panels and EPS," *Energy and Buildings*, vol. 85, pp. 654 – 665, 2014.
- [136] U. Y. A. Tettey, A. Doodoo, and L. Gustavsson, "Effects of different insulation materials on primary energy and CO<sub>2</sub> emission of a multi-storey residential building," *Energy and Buildings*, vol. 82, pp. 369 – 377, 2014.
- [137] U. S. Korsholm, B. Amstrup, T. Boermans, J. H. Sorensen, and S. Zhuang, "Influence of building insulation on outdoor concentrations of regional air-pollutants," *Atmospheric Environment*, vol. 54, pp. 393 – 399, 2012.

## REFERENCES

---

- [138] M. A. Aktacir, O. Buyukalaca, and T. Yilmaz, "A case study for influence of building thermal insulation on cooling load and air-conditioning system in the hot and humid regions," *Applied Energy*, vol. 87, no. 2, pp. 599 – 607, 2010.
- [139] B. P. Jelle, "Traditional, state-of-the-art and future thermal building insulation materials and solutions-properties, requirements and possibilities," *Energy and Buildings*, vol. 43, no. 10, pp. 2549 – 2563, 2011.
- [140] F. Balo, "Feasibility study of "green" insulation materials including tall oil: Environmental, economical and thermal properties," *Energy and Buildings*, vol. 86, pp. 161 – 175, 2015.
- [141] T. Mahlia, B. Taufiq, Ismail, and H. Masjuki, "Correlation between thermal conductivity and the thickness of selected insulation materials for building wall," *Energy and Buildings*, vol. 39, no. 2, pp. 182 – 187, 2007.
- [142] X. Su and S. Xu, "Prediction of varying thermal resistivity of organic insulation materials," *Energy and Buildings*, vol. 71, pp. 137 – 141, 2014.
- [143] Y. T. Huang and W. Tsuang, "Health effects associated with faulty application of spray polyurethane foam in residential homes," *Environmental Research*, vol. 134, pp. 295 – 300, 2014.
- [144] B. B. M. L. D. Stephenson, Andrew Heffron and J. B. Alvey, "Prediction of long term degradation of insulating materials," 2015.
- [145] Sprayfoam Professional. Accessed: 2015.07.15. [Online]. Available: [www.sprayfoam.org](http://www.sprayfoam.org)