CASE BASED ANALYSIS ON POTENTIAL BENEFITS OF CHANGING SRI LANKAN OFFICE BUILDINGS TOWARDS GREEN RATED BUILDING DESIGNS

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Degree of Master of Science

Department of Civil Engineering

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgment any material previously submitted for a degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief, it does not contain any material previously published or written by another person except where the acknowledgment is made in the text.

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Name of the Supervisor: Prof. R. U. Halwatura

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ABSTRACT

Office buildings are one of the main categories of buildings which possess a rapid growth rate in the context of urbanization. They contribute to a major part of energy consumption in commercial building sector. Even though, the need of adopting energy-efficient features arises, the higher initial construction cost and the myth of longer payback period have been made barriers to this movement. Hence, this study focuses on identifying possible energy-efficient strategies, and their economic performance during the life cycle of the building, to perform an Life Cycle Cost (LCC) to compare the total costs incurred in the conventional office building and a green building and to select the best design that ensures the lowest overall cost with high-quality functions.

This study consists of 10 randomly selected low-rise office buildings located in the commercial capital of Sri Lanka, Colombo. Followed by the preliminary survey conducted, it was recognized that high initial cost and the longer payback period was the main two hurdles for the office building owners to move towards the energy-efficient buildings. A conventional office building possesses a 140,000-200,000LKR/m^2 of LCC, and a Building Energy Index (BEI) of around 250 kWh/m^2. Thereafter, based on a defined energy efficient strategy these buildings were developed as energy efficient buildings in 4 stages.

Accordingly, it was concluded that stage 4 platinum level energy efficient building is the best design for a low life cycle cost, and it results in a payback period of 3-4 years, 20%-30% of increment in initial construction cost, 30%-40% increment of maintenance cost and 20%-25% reduction of building LCC compared to the conventional office building design.

Keywords: Building Energy Index, Energy, Energy-efficiency, Life Cycle Cost, Office Buildings

DEDICATION

This dissertation is dedicated to my loving parents, siblings, and my husband.

For their endless love, support, and encouragement given during this journey

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This journey toward a Master of Science Degree would not have been a success if there were not many individuals supported contributing their valuable time for the success of this project.

I am very much grateful to my research supervisors, Prof. Rangika Halwatura and Dr. Nina Danilina for their constant supervision and guidance given during my research period. Their assistance was a vital part of successfully concluding this research.

This research consists of an extensive literature survey and a background study of green buildings and sustainable construction. I owe my gratitude to a long list of researchers who shared their work in numerous ways. Most importantly, I am very much grateful to the management of the office buildings and those who decided to be a part of my research and share their ideas which made my research a success.

Prof. Kumari Gamage, Dr. Nimal Wijayaratnna, and Dr. Kasun Nandapala of the progress review committee, fellow research assistants at Pro-Green Laboratory, Department of Civil Engineering, University of Moratuwa are hereby acknowledged for their appreciation and critical comments which led this research to be more refined. They were crucial in providing a better and a successful output in the end.

Finally, I owe my gratitude to my parents and my family for believing in me, encouraging me, and even supporting me financially when I needed it the most.

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LIST OF ABBREVIATIONS

Abbreviations	Description
ANOVA	Analysis of Variance
BEI	Building Energy Index
EFA	Exploratory Factor Analysis
GB	Green Building
GBCSL	Green Building Council of Sri Lanka
LCC	Life Cycle Cost
PCA	Principal Components Analysis
SEM	Structural Equation Model

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1 INTRODUCTION

1.1 General

The building industry has been identified as a prominent environmental polluting sector causing greenhouse gas emission, noise pollution, global warming, and many more environmental degrading effects. (Chuai et al., 2021) Office building sector is one of the sectors with the highest growth rate during the process of urbanization (Zhou et al., 2018). The operational stage of buildings has become a giant user of energy accountable for a 39% of world energy expenses and a 68% of whole energy consumption in the United States of America (USA) (Y. Li et al., 2021). From the Sri Lankan perspective, electricity use in the commercial building sector is 24% of the total consumption (Rajapaksha, 2019).

Higher operational energy consumption of office buildings has been a vital consideration initiating many types of research recently. Also, energy consumption represents 30% of operating expenses in an office building which puts the spotlight on the importance of a sustainable building (P. Eichholtz et al., 2010). In addressing these concerns, it has been a new trend in moving toward sustainable constructions. Green buildings are one of the trending sectors in building construction since the beginning of the 21^{st} Century.

1.2 Research gap

Even though, the world embraced this newly developed concept of green buildings at the beginning, a reluctance has been recognized recently in investing in a green office building. The primary reason behind this was identified as the insufficient knowledge of the society on the benefits of green buildings throughout the life cycle (Gan et al., 2020). It was found that main building categories moved to green building concepts were instituitional, industrial and commercial sectors rather than residential sector while office buildings were the least among the green rated commercial building sector (Cidell, 2009). Therefore, a need has arisen to enlighten society on the economic benefit of an energy-efficient building during the life cycle. Hence, a systematic method has been adopted in developing a conventional office building into an energy-efficient building leading the study towards a life cycle cost calculation.

1.3 Aims and Objectives

This study aims to develop an innovative, energy-efficient office building model for a lower life cycle cost compared to conventional office buildings. The main objectives of the research are;

1. To identify possible energy-efficient strategies and their economic performance during the life cycle of the building
2. To perform an LCC to compare the total costs incurred in the conventional office building and green building
3. To select the best design that ensures the lowest overall cost with high-quality functions

1.4 Methodology

In this study preliminarily, an online survey was conducted to identify the reasons that hinders the office employees to initiate a move from their conventional office buildings towards energy-efficient buildings. 10 sample cases of low-rise office buildings for the study was identified from the Colombo city, the commercial capital of Sri Lanka, containing the highest density of office buildings.

Selected 10 case studies were directed to a Life Cycle Cost Analysis (LCC) and an energy simulation by the DesignBuilder software version 6.0 to recognize the Building Energy Indices (BEIs) of those existing office buildings. As for the development of these buildings to energy-efficient buildings, a development schedule was designed based on the GREEN$^{SL®}$ tool developed by the Green Building Council of Sri Lanka (GBCSL). Subject to this developed schedule, 10 case studies of the study were designed energy efficiently, in 4 stages. Each stage of each building were subjected to a cost analysis. Therefore, as the main hindrance of the society in moving for energy-efficient buildings, the construction cost, annual savings derive from the newly added energy-efficient features and payback periods were calculated. Based on these 3 main factors, the best low cost energy-efficient office building design was identified and as a further analysis, the LCC deviations of the conventional buildings and the best design were calculated to prove that stage continues to be the best design an office building can achieve irrespective of the initial cost that bears.

1.5 Main findings

In analyzing the existing conventional low-rise office buildings in Colombo, those buildings were bearing a LCC between 140,000 LKR/m^2 to 200,000 LKR/m^2 while having a BEI of around 250kWh/m^2/annum.

In assessing the best design for an energy-efficient office building, the stage 4 platinum radet building was recognized to be the best low cost design, while it bore an inceased 30-50% construction cost for related energy-efficient features installation. But, in the life cycle perspective, this initial high cost can be recovered within 3-4 years of time by setting off all the costs and further years becoming a profit to the organization in an yearly basis. This best design was also again proved by resulting a reduction of 20-25% of LCC when compared to its conventional office building. Hence, it was concluded that stage 4 platinum rated office building is the best energy-efficient office building for the Sri Lankan context.

1.6 Dissertation Structure

Chapter 1 has introduced the motivation, aims, and objectives of this research.

Chapter 2 reviews the relevant literature including the environmental impact of the building sector, sustainable construction, energy efficiency, and life cycle cost analysis.

Chapter 3 includes the methodology and the case development of energy-efficient office buildings.

Chapter 4 provides the results and discussions generated through the analyses done during the development of a low-life cycle cost energy-efficient office building.

Chapter 5 provides the conclusions the study entered and decides which sustainable design is the best to achieve for a low life cycle cost.

2 LITERATURE REVIEW

2.1 General

This chapter describes the base of literature justifying the approach and the direction of this study to achieve its stated objectives. It supports in defining the importance of this study's initiation and how this research has a significant potential to address this stated issue specifically on the energy efficiency and the LCC of office buildings in Sri Lanka. This chapter reviews the environmental impacts of the building sector and the office building sector, sustainable construction, energy efficiency, and reluctance of the society to move towards energy-efficient office buildings.

2.2 Impacts on the environment by the building sector

Buildings demand a higher amount of resources during their construction. The building sector is recognized to be a major sector that contributes to global pollution as a whole (A. S. Weerasinghe et al., 2020). Significant impacts on the environment are caused during the building construction and building operations. Since the manufacturing and transporting processes of building materials and installations during the construction period operate in these buildings, they consume a massive quantity of energy (Geetha & Velraj, 2012). Growing demand for building services, assurance of comfort levels of occupants, and increased time spent inside buildings have confirmed the rising trend in energy demand and it will continue to be increased in the future at an alarming rate, if necessary precautions were not initiated (Halwatura, 2013). Buildings emit an excessive content of CO_2 into the atmosphere during various stages of their life cycles; from the building materials production, building construction, renovations, and rehabilitations until the final demolition (Vyas & Jha, 2018). This is further explained in Table 2.1 below through the analysis of emission of CO_2 according to sector-wise in 2019.

Table 2.1: CO_2 emissions by sector during the year 2019

Sector	Indirect	Direct	Total
Transport	3%	25%	28%
Industry	19%	19%	38%
Buildings	19%	9%	28%
Other	4%	2%	6%

Source: (Vyas & Jha, 2018)

World total building energy consumption has been increasing progressively due to rapid urbanization, climate change, thermal comfort, and other driving factors (X. Li et al., 2019). Buildings have become a gigantic user of energy, being accountable for a 39% of world energy expenses and a 68% of whole electricity consumption in the USA (Y. Li et al., 2021). Lately, the living standard has raised rapidly (Mancini et al., 2020). Energy-saving, carbon emission reduction and pollutant emissions reduction were the priorities for sustainable development in the 21st century (Adhikari et al., 2012).

2.3 Operational energy demand by buildings

Building construction and operational sectors have been recognized as the prominent consumers of resources and raw materials which thereafter lead the way to increased consumption of non-renewable energy regardless of renewable energy. They have also become a significant part of global environmental effects like ozone depletion, urban heat island effect, global warming, etc. at the end (Vyas & Jha, 2018). The rapid growth of energy consumption has raised many concerns over the difficulties in supplies, exhaustion of energy resources, and massive environmental degradations all over time (UNFPA, 2007). Furthermore, the matters identified such as the energy crisis have directed an emerging area of interest in the future of human beings in the world (Adhikari et al., 2012). During the operational stage of office buildings, the Heating, Ventilation, and Air Conditioning (HVAC) system is the main consumer of electricity (38%) from the global perspective. This is because, thermal comfort has become an essential facility recently (González-Torres et al., 2022). However, it is estimated in research that the renewable energy market will be growing at a rate of 1.9% in a year, according to the estimates settled by the International Energy Agency (IEA) and the

National Renewable Energy Laboratory. With the concentration of 70% of the world urbanization in countries recognized as developing countries mostly in Africa and Asia, by 2030, tropical urbanization promotes a significant rising trend in Global GHG emissions. This is because of the reason to the higher usage of non-renewable energy during the lifetime (UNFPA, 2007). Electricity is the most popular mode of energy provider in the world. From that, the share of renewable energies in global electricity generation is nearly 28% by 2020 (IEA, 2020).

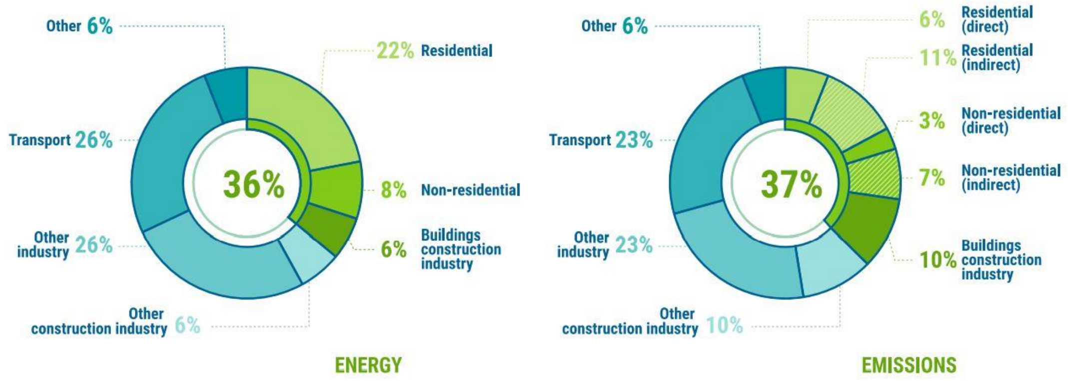


Figure 2.1: Portions of buildings and construction in world energy and energy-related CO_2 discharges

Source: (International Energy Agency, 2021)

According to the International Energy Agency's (IEA) report developed on the building and construction industry and summarized in the above Figure 2.1, in 2020, world-building construction and operations will be collectively accountable for 36% of global energy consumption (International Energy Agency, 2021). Also, the residential sector and non-residential sector respectively amount to portions of 22% and 8% of global energy consumption. Meanwhile, they are also respectively responsible for 17% and 10% of energy-related CO_2 emissions during 2020.

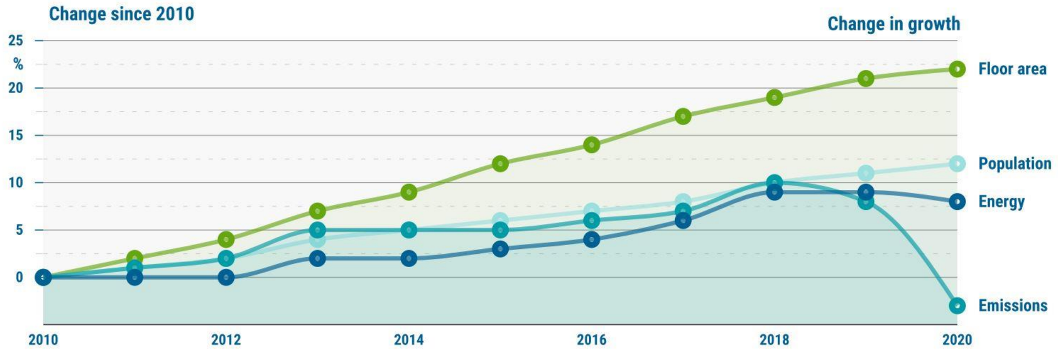


Figure 2.2: Diversion of global trend drivers in building energy and emissions from 2010-2020

Source: (International Energy Agency, 2021)

Figure 2.2, it depicts the growth rate of global building floor space and the population throughout the period from 2010 to 2020. There is a slight decrease in a floor area development in 2020 compared to the growth rate from 2010. However, energy and emissions have decreased rapidly during 2020 mainly due to the Covid-19 pandemic and lockdowns initiated among many countries (International Energy Agency, 2021).

As per a research study done in the New York City, it was concluded that the commercial and industrial sectors' total energy utilization was identified to be lessened by about 7% during the Covid-19 period. Nevertheless, on the other perspective, the household energy utilization had been improved by 23% during March and 10% during April in the year 2020 (Qarnain et al., 2020). Diverse types of buildings usually reveal unique features based on their various functions. As an example, office buildings are mostly furnished with various energy-intensive equipment, and they also often possess a higher demand for space cooling or heating which means the thermal comfort of the occupants. Hence, the office building sector has a comparatively advanced energy consumption per head than the energy consumption of residential buildings (Deb & Lee, 2018). While the building sector is a prominent user of energy in developed countries, office buildings bear a significant portion of it (Junnila et al., 2006). From an economical perspective, the development of commercial buildings contributes nearly half a trillion dollars to the Gross Domestic Product (GDP) of the USA annually. According to Amitrano, in relation to other types of commercial buildings located in

New Zealand, office buildings seize the maximum energy demand intensity per unit floor area per annum ($kWh/m^2/a$) (Amitrano et al., 2014). In determining the distribution of office buildings in the USA, it is 17% of the total non-domestic area and it consumes nearly around 18% of the energy use of total non-domestic energy use. Which on the other hand equivalent to a portion of 3.2% of the total consumption in the country (Pérez-Lombard et al., 2008). Hence, office buildings were recognized as having contributed a significant part of energy in the world due to the fully functioned, extended indoor time (Wijayatunga et al., 2003). In Sri Lanka, the yearly energy utilization of the office building sector in the commercial capital of the country, a typical warm humid city, Colombo, is around 250 $kWh/m^2/a$ (Rajapaksha, 2019). Equally, electricity usage in the office building sector are accounting for 20% of the total electricity usage in the country (A. Weerasinghe et al., 2016). The arguments on climate change and exhaustion of traditional fossil fuels now have simplified the need for a sustainable and more efficient energy system, to reduce the energy consumption and pollutant emission in buildings (Soares et al., 2017).

2.4 Office buildings and environmental impacts

The office buildings sector is the largest subsector of commercial buildings. City centers tend to be filled with a greater number of office spaces recently. Zhou et al., 2018 found in China the total commercial floor space are anticipated nearly to double from 12 billion square meters in the year 2010 to reach 23 billion square meters by the year 2050, while the office building sector occupies 1/3 of total commercial floor space. Recently, Goh et al., 2015 concluded that the commercial building sector consumes an increased running cost than the institutional, residential, industrial, and other buildings. Due to their structure and sizes, the office buildings' constructions result in a noteworthy carbon footprint. Moreover, during the course of their use, they have become a significant source of energy utilization, since that is a place of daily compulsory multi-hour stays for many employees. The total number of office employees in the world is in the hundreds of millions (Grzegorzewska & Kirschke, 2021). The office building sector does have increased energy utilization per head when they are analyzed together with the residential building sector energy use. Since 99% of buildings in the office building sector are being furnished with energy-intensive equipment. Furthermore, they often possess a huge demand for space cooling and heating, which also requires higher energy to fulfill thermal comfort requirements (Deb & Lee, 2018). Research done by Bano & Sehgal, 2018 concluded that cooling and lighting are liable for a majority of the energy utilized in office buildings in India. While active energy efficiency features of office buildings ie. Lighting and HVAC&R facilities have significantly been upgraded by technological progressions. Energy saving through more energy-saving behaviors is being repeatedly neglected (Rafsanjani & Ghahramani, 2020). Adopting energy-conscious practices among occupants is broadly acknowledged as a more economically feasible method of reducing the energy use of the office building sector (Ghahramani et al., 2019).

Apart from higher energy consumption, most recently, Goh et al., 2016 concluded that office buildings are consuming higher operational costs. In other words, there is more operational cost than institutional, residential, and other industrial buildings. However, it is estimated that within the commercial building sector, the operational cost borne by the office building sector differs between 72% to 81% of total costs while in residential buildings it accounts for 69% and in institutional buildings for 52 to 61% (Wong et al., 2010 and Shankar et al., 2011). From a Sri Lankan perspective, electricity consumption in the commercial building sector in Sri Lanka is liable for a portion of 24% of the total electricity consumption of the country. The yearly energy usage in the Colombo office building sector is ~250 kWh/m^2/a (Rajapaksha, 2019).

A study done by Rajapaksha, 2019 assessed BEIs of the office building stock located in six critical Grama Niladhari (GN) divisions in Colombo. A sample size from a division corresponded to a 10-19% of office buildings in each division separately. A mean value has been presented for each GN division. Results have indicated that the BEI differs between235-285 kWh/m^2/a. The peak demand was identified in grama niladhari division, Kollupitiya (Rajapaksha, 2019). Three ranges of BEI distributions have been identified and they were listed as follows in Table 2.2.

Table 2.2: Distribution of BEI ranges of the Colombo office building stock

Levels of BEI Ranges	Percentage Distribution	Values of BEI Ranges
Critical Range (CR)	10.20%	Above 250 $kWh/m^2/a$
Average Range (AR)	54.08%	150–250 $kWh/m^2/a$
Lower Range (LR)	35.72%	100–150 $kWh/m^2/a$

Source: (Rajapaksha, 2019)

The study suggested that the key cost elements of an office building are insurance, administration, taxes, utilities, subsidies, maintenance, and external work. Thus, the involvement of administrative and utility costs has been varying between 30% to 40%. On the other hand, general building maintenance, building services maintenance, taxes and subsidies, and the cost of cleaning varied between 5% to 15% (A. Weerasinghe et al., 2016). Cole & Kernan in 1996 examined the whole life cycle of energy consumption of office buildings, and found the prevalence of operational energy use of buildings. A suggestion was made that substitute designs to decrease operational energy usage have to be taken into consideration, concerning on the assumption made that building energy consumption contributes to numerous environmental problems.

Office employees often spend 8 to 10 hours daily inside the office buildings. It is around 24% of the time they have in an average working week. Therefore, the working environment of these employees is a vital factor. It can directly affect the employees' physical health and mental health and consequently, their productivity. Many recent studies have depicted that the costs experienced by the employer or the building owner (in case if it is a leased building) and the society; since the poor Indoor Environmental Quality (IEQ) of the office buildings, can be a higher cost than the cost that has been allocated for the energy consumption of a building (Al horr et al., 2016). "The quality of the environment of the buildings concerning the wellbeing and health of the building occupants" is the defined term for the IEQ (Elnaklah et al., 2020). Indoor Air Quality (IAQ) in the office affects the health of the employee and their productivity. Employee well-being is a vital factor to be considered by the building management. Concerns should be given in terms of employee health and also the public health research and practices (Singh et al., 2010).

2.5 Sustainable construction

Climate change with its associated disastrous consequences has stimulated the building construction industry to alter towards sustainable construction. Sustainable development is defined as "the development which achieves the needs and necessities of the current generation, without bargaining the capability of the generations in future to meet their own needs" (Sinha et al., 2013). As a result of unfitting construction and operational phases of the building sector, in the 1980s, some organizations had begun efforts in rationalizing architectural and also infrastructural explanations in buildings. This was with the dispersion of the concept of sustainable development (Grzegorzewska & Kirschke, 2021). The last 10–20 years are considered as an era that depicted noteworthy developments in sustainable construction and sustainable building management (Simons et al., 2014). In 1993, the very first Green Building Council was reported to be established, marking the initiation of the global movement toward the green building construction industry. GB evaluation is mainly done by Green Building Rating Tools (GBRT). It is based on the market-based premise. Several options for green building evaluation do exist currently. BREEAM, the Building Research Establishment Environment Assessment Method is the first GBRT. Equally, LEED, Leadership in Energy and Environmental Design created by the United States Green Building Council (USGBC) is considered the most broadly adopted green building rating tool in the world, including in Sri Lanka. The Green Star rating tool is commonly adopted in the context of Australia. BEAM Plus ie. Building Environmental Assessment Method developed by Hong Kong is a leading tool in green building certification (Wu et al., 2020). Green Building Council of Sri Lanka inspires the adaptation of sustainable attempts in Sri Lankan buildings by presenting a green building rating tool; GREEN$^{SL®}$. A green building is generally constructed with the intention to use less water and energy, reduce the life-cycle environmental impacts of the materials used, use a sustainable site, have enhanced indoor air quality, and to resource conservation etc. World Green Building Council (WGBC) and Association of Business Service Leaders (ABSL) statistics together show that, over the past decade or so, office buildings with these parameters at a level of “green buildings” were a continuously rising group, which in some countries it is contributed to 80% of the sector. Furthermore, in Poland, at the beginning of the year 2021, it amounted to a portion of 82.7%, and in Warsaw, office buildings that are certified constituted a portion of 94.3% among all the office buildings present in the country (Grzegorzewska & Kirschke, 2021). Initial investment in energy efficiency at construction stage or renovation stage saves existing resources consumed on waste disposal, energy and water. Then decreases all the other operating costs, it assures the price rises of future energy, and concurrently reduces the emission of greenhouse gasses. The financial benefits occurring from the energy savings and waste reduction are measurable or quantifiable. Nonetheless, many experimental studies recently have focused on environmental problems other than financial performances of the building. Improved IEQ and optimized building design in green buildings have resulted in increased employee productivity and lower absenteeism. But then while energy, water, and other savings are measured exactly, the relationship between the employee productivity and the sustainable building design and operation is very complex to show at an exact figure. The variance between these real and projected building performances is defined as the building performance gap (Wu et al., 2020).

Sustainable building designs are expected to have longer economic lives than conventional buildings (P. Eichholtz et al., 2010). For the past 5-10 years, green buildings are being promoted worldwide, as one of the most sound and effective solutions. They were mainly promoted as a prominent solution to mitigate the aggregation of climate change and global warming effects. Nevertheless, many studies have shown that green buildings are not acting well as it was foreseen or designed. (Wu et al., 2020). Property owners possess a strong interest in the economic valuation and consequences of investments in environmental certification such as green building certifications. The most projecting profit of investments in green building designs was related to the reduced energy usage of the building (Harrison & Seiler, 2011).

2.6 Life cycle costing of buildings

"The cost of a certain asset and/ or parts of it, during its defined life cycle, that is comprised of all the phases since construction through operations and maintenance to the disposal" is the most descriptive definition of the LCC. Following Figure 2.3 replicates the boundary of a building in an LCC calculation.

Net present value (NPV) is the mainly used economic evaluation method for LCC (S. Li et al., 2020). Economic evaluation methods like LCC, which accounts for savings and expenditures of developments throughout their predicted life cycle, have been used broadly in the USA. It was used in government decision-making on large projects. An example, for water resource investment projects (Goh & Sun, 2015). The facility owner's total cost will be assessed by the LCC. It accounts for each and every cost that occurred, from the stage of owning to the disposing of the building or a building system. When the project alternatives to fulfill the same performance, requirements expected from the building, nonetheless vary with the initial construction costs or investment and operations costs, LCC is mostly suitable for the use. A comparison of those two aspects of costs should be conducted, on a scale in order to find out the best economically sound solution that maximizes net savings at the end of the project. Lowest LCC is the most forthright and concise way of economic evaluation. (Fuller, 2006). The optimal design can be obtained by minimizing the total expected LCC by using a mathematical procedure (Wen et al., 2001).

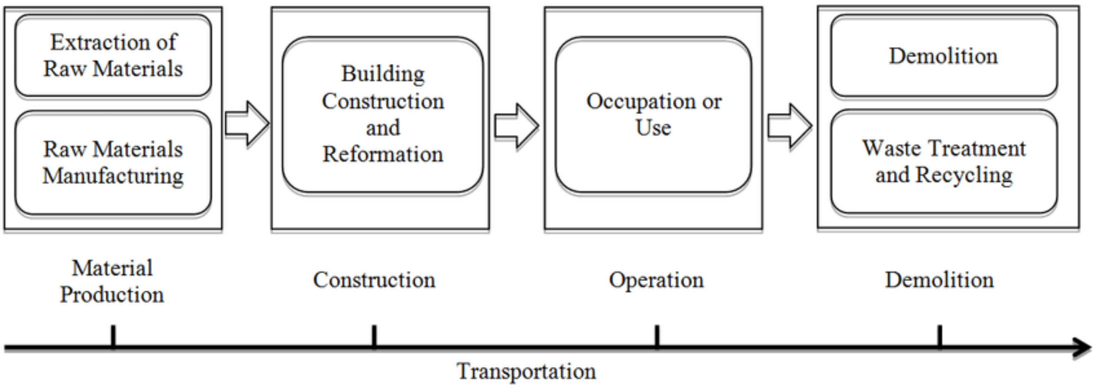


Figure 2.3: Life cycle of a building

Source: (W. Wu et al., 2014)

The "system boundary" of a life cycle of a building, determines the processes that need to be included in the LCC. This demarcation of the system or the study boundary shall be consistent with the study objectives and limitations of the LCC study (Pan et al., 2018). Already demarcated system boundary models that are in practice are cradle to grave, cradle to gate, gate to gate etc. However, the definitions and extents of the adopted LCC differ from one study to another, which means a system boundary is subjective to each case separately (Pan et al., 2018). LCC of a building is a sum of all the costs within the system boundary as in Equation 2.1.

LCC = I + Repl + E + W + OM&R + O — Res   Equation 2.1

- LCC = Total LCC in present-value (in present value)
- I = Initial cost
- Repl = Present value of replacement costs
- E = Present value of energy consumption costs
- W = Present value of water consumption costs
- OM&R = Present value of maintenance and repair costs
- O = Present value of other available costs
- Res = Present value of disposal costs

$$\boldsymbol{PV = FV \left[\frac{1}{(1+i)^n}\right]}$$ Equation 2.2

- PV = Present value
- FV = Future value of expected expenses
- n = Time period in years between the time of analysis and time of expense
- i = Inflation rate

For adding and comparing the cash flows that were sustained at diverse stages of the life cycle of a study, cost values should be made, time equivalent as in Equation 2.2. This means, the LCC system adapts those values into present values by way of discounting them into a mutual and decision point in time, which is also known as the "base date of the calculation". The interest rate that was used for the discounting process is the rate that reproduces an investor's opportunity cost of money over time. In other words, the investor can obtain a return as high as that of his next best investment. Therefore, the discount rate represents the investor's least adequate rate of return (Fuller, 2006).

2.7 What hinders to move toward green building construction

One of the demands clients make is a guarantee on the continuing economic performance and costs of these green constructions, and this assurance is nowadays expected during the initial period of the green building construction project. The building construction supply chain consists of developers, manufacturers, designers, and constructors. They have become subject to a massive burden to cut the whole project expenses to occur and also concentrate on the cost, over the life cycle of the building (Öberg, 2005). The interest in green building construction is far below the projected level because of the high initial cost that attributes even though the perception of green building has been applied to the building construction industry bearing the intention of promoting the operational efficiency of the building and reducing financial costs (Goh & Sun, 2015). Lack of proper awareness in the society on the major cost savings expected during the operational period of the green building, undervaluing of the possible cost savings, and overestimation of the invested expenses of energy-efficient practices have guided the society to deviate from taking the first step towards green buildings construction or conversion of an existing conventional building to a green building (Ala-Juusela et al., 2014). Moreover, both private and public organizations during their decision-making process, tend to base their decisions on investments to construct or convert to a green building simply by relying on the initial construction cost. They do not consider the expected life cycle cost of the green building. Which explains the extent of economic benefits to be expected during the operational period of the green building (Al-Hajj & Horner, 2008). In many types of research, it was concluded that the initial cost of a green building is considerably greater than the conventional building, whereas it results in an opposite pattern in the cost of operations of the building (A. S. Weerasinghe et al., 2021, Eichholtz et al., 2010).

In Sri Lanka, it is identified that an inadequate number of buildings have been certified for the implementation of green features and the reason behind the back for the comparatively lower number of buildings was the associated higher initial cost (A. S. Weerasinghe et al., 2021). Further, the investors investing in green buildings have failed to appreciate the subsequent benefits, not only environmental and social but also economic advantages acknowledged by green buildings during their operations. Waidyasekara & Fernando, 2013 specified that the added construction cost for a green building is known to be the principal hurdle that hinders the execution of green buildings in Sri Lanka. Hence, the findings of this study have enabled green investors to take well-versed decisions and encourage an advanced level of sustainability in the end.

Evidence has shown that green buildings do defeat conventional buildings in various aspects of the routine. However, the initial cost at the face of a green building project is frequently quoted as the snag to the spread of the green building development. A study done by Dwaikat & Ali, 2016 concluded that a noteworthy gap resulted in the cost premium range. Among the reported green cost premiums, over 90% of premiums were reported between a range of 0.4% to 21%.

Table 2.3: Construction costs by BREEAM rating tool (cost per gross m^2)

Certification	**(Cost)**	**(Cost)**	**(Cost)**	**(Cost)**	**(Length)**
Outstanding	0.380	0.307	0.347	0.305	
	[0.220]	[0.210]	[0.191]	[0.183]	
Excellent	0.189	0.101	0.078	0.047	
	[0.034]	[0.033]	[0.034]	[0.036]	
Very good	0.185	0.136	0.132	0.099	
	[0.047]	[0.046]	[0.046]	0.041]	
Good	-0.008	-0.052	-0.076	-0.070	
	[0.107]	[0.090]	[0.089]	[0.076]	
Pass	0.120	0.060	0.069	0.051	
	[0.221]	[0.187]	[0.182]	[0.175]	
Outstanding/ excellent/ very good					0.130

					[0.067]
Good/ pass					-0.056
					[0.105]
Building size		Yes	Yes	Yes	Yes
Build-out-extent		Yes	Yes	Yes	Yes
Primary materials			Yes	Yes	Yes
Building use			Yes	Yes	Yes
Client			Yes	Yes	Yes
Contract competition				Yes	Yes
Tender process				Yes	Yes
Contractual cost sharing				Yes	Yes
Building function fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Constant	7.256	6.871	6.974	7.015	-0.838
	[0.108]	[0.109]	[0.111]	[0.139]	[0.302]
Observation	2379	2379	2379	2379	825
R-squared	0.324	0.374	0.408	0.472	0.693
Adj R2	0.29	0.34	0.38	0.44	0.64

Source: (Chegut et al., 2019)

In the study by Chegut et al., 2019, this Table 2.3 showed that the marginal construction costs of green buildings were rated by using the BREEAM rating tool in the United Kingdom. It explains that, when the building increases its certification level, then the initial cost difference between those certification levels is substantial. Based on the four model specifications that were employed, “outstanding” level buildings are around 30% - 38% expected to be more expensive than the conventional building. Two buildings were rated and one building as “excellent” and the other building as “very good”, the initial cost premium ranged between 5% to 19%, and last, for the least two green certification levels, statistically significant green building cost premiums were not found, irrespective of the model specification. This resembles the obtuse acceptance of more efficient green buildings performing properly. Which in other terms is a market barrier for green projects. This study further suggested that the expected savings can be increased if advanced green building practices and innovations by using digital technology are adopted.

In the conclusion of a survey conducted, the three top main obstacles expected in green building construction that was encountered by the professionals were high-cost premium, absence of communication between the allocated project members, and the absence of client's curiosity or the market demand as also shown in Table 2.4 (Hwang & Tan, 2012).

Table 2.4: Obstacles encountered during green buildings project management

No	Obstacles	Frequency	Percentage (%)
1	High cost premium of green building project	31	100.0
2	Lack of communication and interest amongst project team members	26	83.9
3	Lack of required expertise in green building	0	0.0
4	Lack of knowledge regarding green building principles	0	0.0
5	Lack of management and time to implement green construction practices	8	25.8
6	Lack of expressed interest from client and market demand	16	51.6
7	Lack of expressed interest from other project team members	12	38.7
8	Resistance to change from conventional to green practices by company's employees	11	35.5
9	Lack of government's support (e.g. incentives) for sustainable construction	0	0.0
10	Green building practices are costly to implement	24	77.4
11	Lack of information regarding green products and building systems	9	0.0
12	Lack of credible research on the benefits of green buildings	21	67.7
13	Complex codes and regulations on green building and sustainable construction	7	22.6

Source: (Hwang & Tan, 2012)

To overcome this problem of the cost of green buildings, the respondents of the survey themselves have suggested that a boost of green buildings by the government will encourage the investors and building owners to move towards green buildings more. It will help in offsetting the high cost. The government's appreciation of these projects is an important initiative to encourage the building sector. 67.7% of respondents of the survey have suggested that societal education on the green building will be the baseline to induce at least the future generation with an environmentally sound mind. Therefore, knowledge should be given on the cost and benefit performance of the green buildings as well (Hwang & Tan, 2012).

2.8 Life cycle cost analysis of green buildings

Research regarding incremental costs of green buildings is quite limited number which is present in the emerging body of literature regarding green buildings, due to the limitation of data access, (L. Zhang et al., 2018). Based on the Triple Bottom Line (TBL) theory, it is crucial to consider these three elements; environment, society, and economy, to guarantee the sustainable development of the built environment. Sustainability lies at the heart of a process in evaluating not only the natural environment but also the economic and social aspects. (Mangialardo et al., 2019). Sustainable life cycle building management has been suffering from the absence of life cycle data. Even though numerous studies have spoken about life cycle costing in their case studies, only a limited number of studies included a larger set of comprehensible data (Haugbolle & Raffnsoe, 2019).

The main savings green building occupants receive are the cost-savings that are gained through reduced energy, and water consumption and lower operational and maintenance costs (X. Zhang, 2015). United Nations Program has reported that a 30% - 80% reduction of energy utilization of buildings can be attained possibly if the correct green techniques are applied. Moreover, according to the World Green Building Council reports, the green building design itself impacts the health, well-being, and productivity of the occupants of the building. Hence, green buildings are not only limited to environmental benefits but also expand to social and financial benefits to key stakeholders (Hwang et al., 2017).

Irrespective of the direct benefits attached to the lower operating cost, there are incremental benefits of four other categories of green buildings such as improved thermal comfort, increased health and productivity, increased market value, greater corporate reputation, and also a positive environmental externality (X. Zhang, 2015). However, these four other benefits are not easily quantifiable to get an exact monetary value, but they do improve the work performance of the building occupants in the end. Adopted green attributes for the building bear the potential to enhance the indoor environmental quality, thus resulting in healthier and eventually, an increasingly satisfactory level of performance from more productive occupants (World Green

Building Council, 2014). On the other hand, renting, developing, or purchasing green buildings will indicate an enterprise's assurance towards the environment and also their obedience to the Corporate Social Responsibility (CSR) requirement, which then leads the way to the enterprise that can gain a prominent corporate reputation to the organization (P. M. A. Eichholtz et al., 2016).

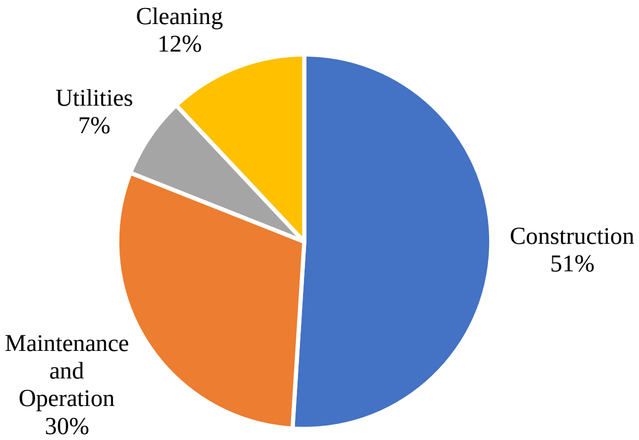


Figure 2.4: Distribution of life cycle cost of an office building

Source: (Haugbolle & Raffnsoe, 2019)

The findings of Haugbølle & Raffnsøe, 2019 as shown in Figure 2.4, suggest that the operational costs of an office building are being dispersed by nearly 1/3 of the life cycle costs, which are casing maintenance and operations. Similarly, the residual 1/5 of the life cycle costs have been alienated as the cleaning costs and both energy cost and water cost in a ratio of 2:1. In a Sri Lankan case study done by A. S. Weerasinghe et al., 2021 it was determined, that the initial cost attached to a green building amount to 37% more advanced than the conventional building of the same, whereas the green buildings do offer respective savings of 22%, 28% and 11% during the maintenance, operation, and the disposal costs. Subsequently, it was found after a sensitivity analysis that had been performed, that green industrial buildings possess an overall saving of 21% during their life time and hence, they are economically more sustainable compared to conventional buildings.

In Bombugala & Atputharajah, 2012 it was concluded that even though the initial investment in green buildings is comparatively 20% to 25% greater than conventional buildings, the economic benefit gained during the life of the building was ten times higher than the operational stage of the building.

In considering office employees, the IEQ of the office building directly affects the health, well-being, and productivity of the employees. IEQ can cause several physical impacts like asthma exacerbation and respiratory allergies. The movement toward this green building concept has addressed this and it was found by many types of research that the improved design, thermal comfort, and aesthetic appearance have caused the employees to improve their productivity by making a stress-free and healthy environment (Singh et al., 2010). Even though these social benefits are not quantitative as such in energy and water savings, these benefits provide a substantial motivation to convert the building construction industry to green.

2.9 Summary

Building sector is a prominent environmenatally disturbing sector from its construction stage even until its disposal stage. Operational stage of a building has been identified as one of the crucial stages in which many environmental polluting activites have occurred in fulfilling their needs like energy, thermal comfort, water consumption, waste management etc. When considering operational energy of a building, office buildings possess a higher responsibility since this sector is having a fully conditioned and functioned hours a day. Recently, energy consumption of office buildings have been identified as one of the vital concerns that needs proper attention since office spaces are one of the fastest growing building sector in the current world.

Even though, the concept of sustainable construction emerged year back, the trend of moving the construction industry has been decelerated due to the high costs attached to it. This misconception has become the major hurdle for the employers in office building sector in the world too. In Sri Lankan context, office buildings are being one of the rising building sector, a proper addressing of this hurdle is much needed in moving the office buildings mainly towards the energy-efficiency.

3 DEVELOPMENT OF AN ENERGY-EFFICIENT OFFICE BUILDING FOR A LOW LIFE CYCLE COST

3.1 General

This chapter defines the process of developing an energy-efficient building subject to a specific developing scheme derived from the GREEN$^{SL®}$ rating tool presented by the GBCSL. Here, it explains how the sample was selected, what building design is the best design which gives the maximum energy saving performances while providing the least life cycle cost of the building through reduced operational cost savings.

3.2 Identification of the research sample

Sample selection criteria were developed based on a literature survey conducted and a preliminary walkthrough survey. During this stage, the dispersion of the buildings and building types were identified.

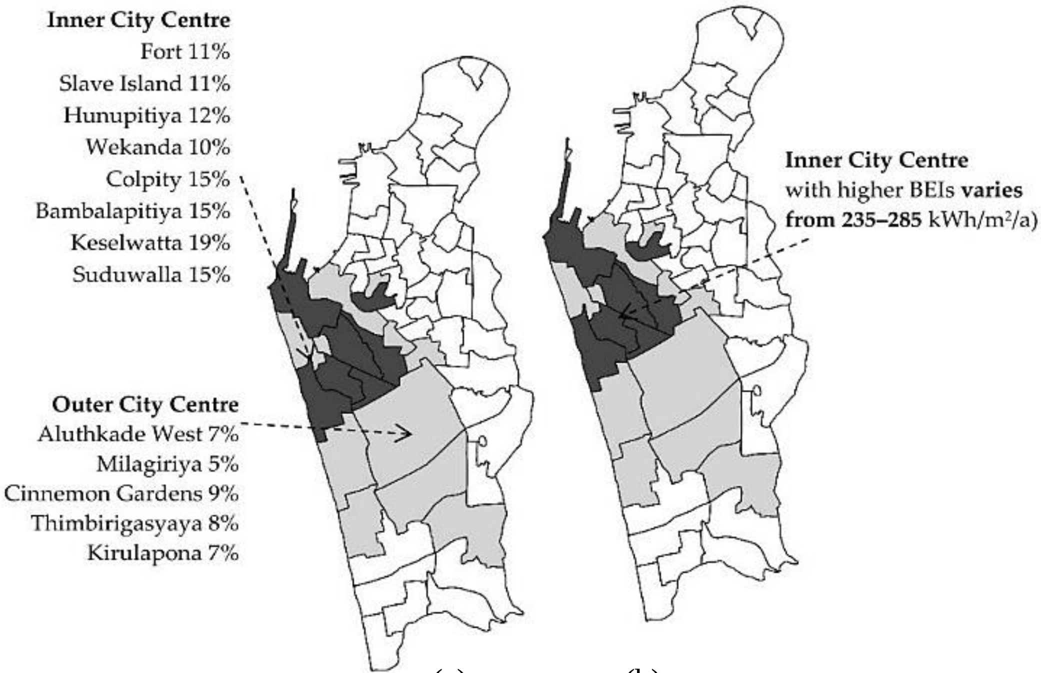
3.2.1 Focused building sector and the region

This current emerging demand for office spaces in Sri Lanka itself spoke the option of office buildings to be considered as the focus area of this study. The annual energy consumption of office buildings located in the commercial capital of Sri Lanka, Colombo is ~250 kWh/m^2/a (Rajapaksha, 2019). Therefore, the office building sector was considered as it is one of the building sectors which contributes to the higher consumption of energy in the world due to its high usage of energy-intensive equipment and high demand for heating and cooling conditions (Deb & Lee, 2018).

When this office building sector is concerned, being the highest office space dense region in Sri Lanka, the Colombo City region was identified also as the commercial capital of Sri Lanka *(Rajapaksha, 2019)*. Colombo City was selected as the focu sed region for the study.

Below Figure 3.1 is the "a" map of Colombo City and the distribution of office building stock in the city. Map "b" represents office buildings consisting of higher building energy indices (BEI). Accordingly, the BEIs vary between 235 – 285 kWh/m^2/a.

therefore, this study done by Rajapaksha, 2019 justifies the selection of this region, Colombo city as the focal study area for the research.



(a) (b)

Figure 3.1: Dispersion of office building stock in Colombo Metropolitan Region (a.) Office building stock dispersion within Colombo (b.) Buildings with higher Building Energy Indices (BEI) in the inner city center
Source: (Rajapaksha, 2019)

3.2.2 Selection of building design typology

Colombo is filled with many low-rise buildings until around 2005. Then, new high-rise buildings started to grow rapidly with the urban development (Johansson & Emmanuel, 2006). A "Low-rise building" can be defined, as a building consisting of a ground floor and 5 or less than 5 upper floors (Bahramian & Yetilmezsoy, 2020). In a study done in Shanghai, it was found that office buildings are accountable for more than 25% of the existing commercial building stocks. Furthermore, office buildings that are located in Shanghai, are comprised of more than 50% of low-rise office buildings (Hong et al., 2020). Therefore, this research narrowed down its scope to low-rise office buildings as the building typology to represent the majority of office buildings stock in Colombo to address them in converting or constructing them into more energy-efficient buildings.

3.3 Sample selection

Based on the above-developed sample selection categories and further concluded criteria, 10 low-rise office buildings were to be selected for the study purposes. The decided building selection criteria are as follows;

- Building location – within Colombo city
- An office building
- A low-rise building
- Not a building rated as a green building
- Occupant Density – not a densely occupied space
- The main function of the building should be administration/ management/ information and technology (IT) sector/ banking etc.
- Availability of data
- Access to the data

3.4 Face-to-face interviews held with conventional office buildings

During the walkthrough survey done mainly focusing the Colombo City, face to face interviews were conducted with office employees at the offices that were initially contacted. Based on these interviews, a series of questions were asked on what are the administrative backgrounds and what is their perception of energy efficiency in their office building. Following these interviews, the main suggestions mentioned below were pointed out.

3.5 Employee perception of converting an existing office building into a green building

This view was taken based on an online survey carried out targeting the audience of office employees to assess their perception of "What hinders converting your existing office building to a green building?". A comprehensive literature survey has been initially conducted to identify potential barriers to converting existing buildings to energy-efficient buildings. Based on the literature survey, a well-designed questionnaire (vide Appendix A) was used to collect the accurate process of social phenomena. This was designed mainly in three core sections:

- Section 01: Building description (Office category, location, building size)
- Section 02: Demographic information of the respondent (Age, gender, designation, educational level),
- Section 03: Evaluation of the identified 25 barriers of the relevant office building to convert it to an energy-efficient building.

The opinions gathered via the survey were rated using a five-point Likert scale as in 1: Strongly disagree, 2: Agree, 3: Neutral, 4: Agree and 5: Strongly Agree. The technique of the five-point Likert scale was preferred among others since it allows the respondents to express their thoughts effortlessly.

50 low-rise office buildings were selected within the Colombo area, which is the commercial capital of Sri Lanka based on a random sampling technique. Decision-making employees of the office buildings were contacted from each office. There were 150 responses obtained from 50 randomly selected low-rise office buildings. Data analysis was done in 2 phases by way of elaborative and inferential analysis using the Statistical Package for Social Science (SPSS) 29.0 and establishing an initial Structural Equation Model (SEM) using SmartPLS 3.3.7 software.

The descriptive statistical analysis in phase 1 was conducted by defining the central tendency (sample mean: $\bar{x}$) and the standard deviation (sd: σ) (Rodriguez-Nikl et al., 2015). The inferential analysis was done by conducting a one-way analysis of variance (ANOVA) test and exploratory factor analysis (EFA). One-way ANOVA was conducted to determine whether,

- The decision-makers from different office buildings had varied perspectives about the identified challenges,
- To evaluate which of the EFAs could lower the number of challenges(variables), and
- To determine the relevant variables

Principal Components Analysis (PCA) was held as the key factor analysis, and Varimax was used as the rotation method (Rodriguez-Nikl et al., 2015). To assess the factor analysis' applicability, The Kaiser–Meyer–Olkin (KMO) and Bartlett sphericity tests were used. Bartlett's sphericity test was conducted to test if the correlation matrix was significantly different from zero and whether the KMO coefficient should be greater than 0.7 (Rodriguez-Nikl et al., 2015).

In phase 2, PLS-SEM is capable to solve complicated issues deprived of the need for a significant number of samples (Alcaraz-Corona et al., 2019). SmartPLS 3.3.7 software was used to establish Initial hypothetical PLS-SEM in this study.

3.6 Life Cycle Cost (LCC) calculation of conventional office buildings

Selected 10 low-rise office buildings were subjected to an LCC calculation to gain an overall knowledge as to how these buildings' life cycle costs have been distributed.

3.6.1 Definition of the system boundary

In an LCC calculation definition of the system boundary is an important aspect. The system boundary of a life cycle of a building determines the processes that need to be included in the LCC. It needs to be consistent with the stated objectives and limitations of the LCC study (Pan et al., 2018) and can be subjected to the limitations of the study. Following Figure 3.2 defines the adopted system boundary for the study based on the above limitations and the objectives for the sustenance of the research without deviating the process from its focused analyzes.

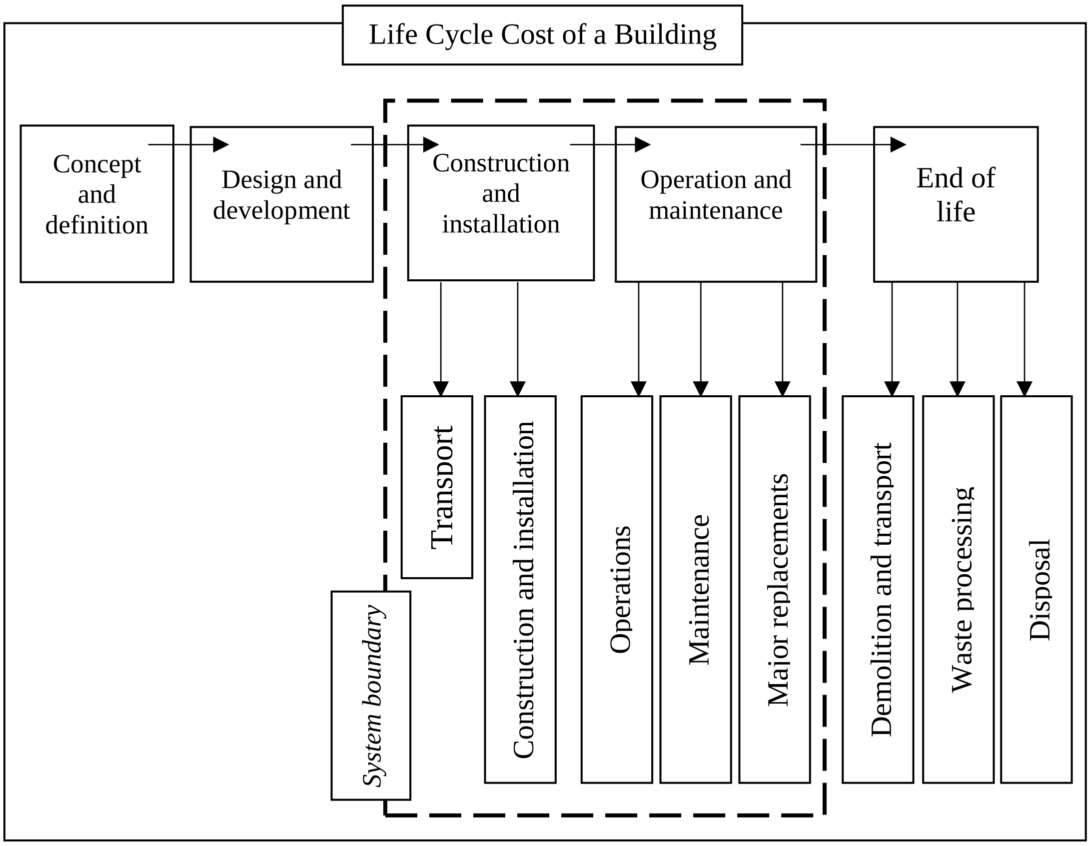


Figure 3.2: System boundary of the study

3.6.2 LCC Calculation

LCC calculation is based on the assumptions made to avoid limitations and accomplish the objectives set out in the study. The LCC was obtained based on the following Equation 2.1. For it, the future values, which means the values that occurred after the base year of the project will be set in the present value after the discounting of the values to a future date. The conversion of a future value to a present value is depicted in Equation 2.2.

3.6.3 Assumptions based on the LCC calculation

Depending on the objective of the study and literature following assumptions were made to calculate the LCC of a building case.

- LCC Calculation is limited to the defined system boundary for all buildings.
- LCC was done assuming that the building was constructed year as the base year for the calculation (A. S. Weerasinghe & Ramachandra, 2018).

- The life span of an office building was considered to be of 50 years based on literature (Robati et al., 2018).
- Major replacement costs were included in the maintenance cost and considered based on cumulative periodical expenses for major replacements over 5 years due to the limited availability of data.
- All calculations were made based on the building operational expenditures that occurred during 2018 and 2019.
- 4% was considered as the inflation rate for the discounting of future values. This was taken as per the central bank reports and 4% is the average inflation rate of Sri Lanka before 2020 (Central Bank Sri Lanka, 2019).
- Inflation and expenditure data were neglected from the year after 2020 due to the higher fluctuation of the inflation and prices due to the economic crisis that Sri Lanka faced after 2021.

3.7 Energy simulation of conventional office buildings

Energy simulation of the above selected 10 conventional office building cases was done by using the DesignBuilder software version 6.0. This software provides the BEI of the simulated building. BEI is the amount of total energy usage of a building, for one year, measured in kilowatt-hours per gross floor area (m^2) (Moghimi et al., 2011). Rajapaksha has stated that an average office building's BEI varies between 235-250 $kWh/m^2/a$. (2019)

To feed the DesignBuilder software with the related data, the following construction-related data were identified by the observation and data collection done by the building staff and the owners. The summarized data set is shown in the following Table 3.1.

For the activity tab data in DesignBuilder software, as depicted in Table 3.2, main data required as to their main function, work profile (working days a week), number of floors in the building, and working schedule were obtained during the initial discussion with the selected buildings while data like clo-values, metabolic factor, and lux level were obtained through literature and DesignBuilder manual as average values for an office sector building (Occupational safety and health branch Labour department, 2016), (DesignBuilder Software, 2009).

Table 3.1: Construction tab - Data collection for the energy simulation

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Walls	Cement Block wall 150mm	Brick wall 225mm	Cement Block wall 150mm	Brick wall 225mm	Brick wall 225mm	Brick wall 225mm	Cement Block wall 150mm	Cement Block wall 150mm	Brick wall 225mm	Cement Block wall 150mm
Columns	Concrete	Concrete	Concrete	Concrete	Concrete	Concrete	Concrete	Concrete	Concrete	Concrete
Doors/ Windows	Aluminum + Glass	Aluminum + Glass	Aluminum + Glass	Aluminum + Glass	Wood + Glass	Aluminum + Glass	Aluminum + Glass	Aluminum + Glass	Aluminum + Glass	Aluminum + Glass
Wall plaster	Cement/ sand Plaster	Cement/ sand Plaster	Cement/ sand Plaster	Cement/ sand Plaster	Cement/ sand Plaster	Cement/ sand Plaster	Cement/ sand Plaster	Cement/ sand Plaster	Cement/ sand Plaster	Cement/ sand Plaster
Floor	RC slab 5in + Plaster +Tile	RC slab 4in + Plaster +Tile	RC slab 5in + Plaster +Tile	RC slab 4in + Plaster +Tile	RC slab 5in + Plaster +Tile	RC slab 4in + Plaster +Tile	RC slab 4in + Plaster +Tile	RC slab 4in + Plaster +Tile	RC slab 5in + Plaster +Tile	RC slab 4in + Plaster +Tile
Staircase	Concrete + Tile	Concrete + Tile	Concrete + Tile	Concrete + Tile	Concrete + Tile	Concrete + Tile	Concrete + Tile	Concrete + Tile	Concrete + Tile	Concrete + Tile

Table 3.2: Activity tab - data collection for the energy simulation

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Main function	Administr-ative work	Banking	IT Firm	Administr-ative work	Administr-ative work	Administr-ative work	Administr-ative work	Administr-ative work	Administr-ative work	IT Firm
Working profile	5	5	5	5	5	5	5	5	5	5
No: of floors	G + 5	G + 2	G + 4	G + 5	G + 4	G + 3	G + 3	G + 3	G + 3	G + 3
Clo-value	0.665	0.665	0.665	0.665	0.665	0.665	0.665	0.665	0.665	0.665
Metabolic factor	0.925	0.925	0.925	0.925	0.925	0.925	0.925	0.925	0.925	0.925
HVAC	VRF (Air-cooled), Heat Recovery, DOAS	VRF (Air-cooled), Heat Recovery, DOAS	VRF (Air-cooled), Heat Recovery, DOAS	VRF (Air-cooled), Heat Recovery, DOAS	VRF (Air-cooled), Heat Recovery, DOAS	VRF (Air-cooled), Heat Recovery, DOAS	VRF (Air-cooled), Heat Recovery, DOAS	VRF (Air-cooled), Heat Recovery, DOAS	VRF (Air-cooled), Heat Recovery, DOAS	VRF (Air-cooled), Heat Recovery, DOAS
LUX level	300	300	300	300	300	300	300	300	300	300

3.8 Assessing the current green building state of conventional office buildings

As the next step, the selected 10 conventional office buildings were rated by using the GREEN$^{SL®}$ rating tool initiated by the Green building Council of Sri Lanka (GBCSL). This was done based on the points criteria stated in the green building rating tool for the existing performances of the selected conventional buildings. Hence, it gives an overall idea as to how these buildings perform and to what extent they are environmentally beneficial compared to other office buildings. This rating will be subjected to the points allocated for respective categories; sustainable sites, management, water efficiency, energy and atmosphere, materials and resources, indoor air quality, innovation and design process, and social and cultural awareness. Total points will be allocated as; 0-40 non-certified, 40-49 certified, 50-59 silver, 60-69 gold, and 70 and above platinum level buildings.

3.9 Development of the energy-efficient strategy to improve conventional buildings to energy-efficient buildings

In the phase of the development of an energy-efficient strategy to improve existing buildings into energy-efficient buildings, the GREEN$^{SL®}$ rating tool was selected since it was the tool developed by Sri Lankan GBC considering the Sri Lankan context.

3.9.1 Identification of energy-related features in the GREEN$^{SL®}$ rating tool

To develop the selected sample of 10 conventional office buildings into energy-efficient office buildings, a development strategy has to be created. Hence, for this purpose based on the GREEN$^{SL®}$ rating tool firstly, energy efficient features listed in it were extracted. Then, they were arranged in the same respective order as they were in the rating tool. The tables Table 3.3 and

Table 3.4 below, show the extracted energy-efficient features which were rearranged in ascending order in two separate phases as features directly affecting the energy consumption of the building and feature indirectly affecting the energy consumption of the building. As a whole, 28 points of direct features were identified and 37 points of indirect features were identified.

Table 3.3: Direct features that are affecting the energy consumption of the building

Main section	Direct features		28
1	1.1.1	Optimizing occupant comfort and Energy Efficiency	1
2	2.11	Light Pollution Reduction	1
3	3.6	Innovative Water Transmission	1
4	Prerequisite 1	Fundamental Building Systems Commissioning	Required
	Prerequisite 2	Minimum Energy Performance	Required
	Prerequisite 3	CFC Reduction in HVAC & R Equipment	Required
	4.1	Optimize Energy Performance	1-10
	4.2	Renewable Energy	1-6
	4.3	Additional Commissioning	1
	4.5	Measurement & Verifications	1-2
	4.6	Green Power	1
	4.7	Certified Energy Auditor	1
5	5.1.7	Global Warming Potential of buildings	1
6	Prerequisite 1	Minimum IAQ Performance	Required
	6.6.1	Lighting controls	1
	6.7	Thermal comfort, design	1
	6.8	Thermal comfort, verification	1

Table 3.4: Indirect features affecting the energy consumption of the building

		Indirect features	37
2	2.6.1	Protect or Restore Habitat	2
	2.6.2	Vertical greening	2
	2.7	Storm Water Design, Quantity Control	2
	2.8	Storm Water Design, Quality Control	2
	2.10	Heat Island Effect, Roof	1
3	Prerequisite 1	Eliminate potable water consumption for irrigation and landscaping	Required
	3.1	Use of alternative water sources	1
	3.2	Use of water-saving performances	1
	3.3	Indoor water use reduction	1-4
	3.4	Water Efficiency in air conditioning system	1
	3.5.1	Reduce Potable Water Use	1
	3.5.2	Reduce Potable Water Use or Treat Wastewater	1
	3.5.3	Harvested rainwater	2
	3.5.4	Aquifer Recharge	1
4	4.4	Ozone Depletion	1
5	5.1.1.1	Maintaining 75% of Existing Building Structure and Shell	2
	5.1.1.2	Maintaining 75% of Existing Building Structure and Shell and 25% of Non-Shell Areas	1
	5.1.2.1	for at least 10% of the Building	1
	5.1.2.2	for at least 20% of the Building	2
	5.1.3	Recycled Content	1
	5.1.4	Local/ Regional Materials	1
	5.1.5	Rapidly Renewable materials	1
	5.1.6	Certified wood and other building materials	1
	5.1.8	Materials Produced with Waste materials	1
	6.2	Increased Ventilation	1
	6.6.2	Comfort controls	1
	6.9.1	Daylight	1
	6.9.2	Views	1

3.9.2 Development of the stage-wise case development schedule

It was decided to improve these existing conventional buildings into energy-efficient buildings from the non-certified level to the platinum level based on the strategy. To define the number of stages and in what portion they have to be applied, a case development schedule was declared.

The following Table 3.5 depict the case development schedule that had to be applied for all the 10 cases of conventional building sample selected.

Table 3.5: Case development schedule

Current status	**Non-certified**		**Certified**		**Silver**		**Gold**	
Achieving	Directly affecting energy	Indirectly affecting energy	Directly affecting energy	Indirectly affecting energy	Directly affecting energy	Indirectly affecting energy	Directly affecting energy	Indirectly affecting energy
Stage 1 (Certified)	25%	25%						
Stage 2 (Silver)	25%	25%	33%	33%				
Stage 3 (Gold)	25%	25%	33%	33%	50%	50%		
Stage 4 (Platinum)	25%	25%	33%	33%	50%	50%	100%	100%

Table 3.6: Application of the case development schedule

Features directly affecting on energy			**Features indirectly affecting on energy**	
18			37	
Optimizing occupant comfort and energy efficiency	1	**Stage 1**	Protect or restore habitat	2
Light pollution reduction	1		Vertical greening	2
Innovative water transmission	1		Storm water design, quantity control	2
Fundamental building systems commissioning	Rqd		Storm water design, quality control	2
Minimum energy performance	Rqd		Heat island effect, roof	1

CFC reduction in HVAC&R equipment	Rqd		Eliminate potable water consumption for irrigation and landscaping	Rqd
Renewable energy – I	1-2		Use of alternative water sources	1
Renewable energy – II	3-6	**Stage 2**	Protect or restore habitat	1
Additional commissioning	1		Indoor water use reduction	1-4
			Water efficiency in air conditioning system	1
			Reduce potable water use	1
			Reduce potable water use or treat wastewater	1
Measurement & verifications	1-2	**Stage 3**	Harvested rainwater	2
Green power	1		Aquifer recharge	1
Certified energy auditor	1		Ozone depletion	1
Global warming potential of buildings	1		Maintaining 75% of existing building structure and shell	2
			Maintaining 75% of existing building structure and shell and 25% of non-shell areas	1
			For at least 10% of the building	1
			For at least 20% of the building	2
Minimum IAQ performance	Rqd	**Stage 4**	Recycled content	1
Lighting controls	1		Local/ regional materials	1
Thermal comfort, design	1		Rapidly renewable materials	1
Thermal comfort, verification	1		Certified wood and other building materials	1
Optimize energy performance	1-10		Materials produced with waste materials	1
			Increased ventilation	1
			Comfort controls	1
			Daylight	1
			Views	1

Since all the cases of conventional office buildings are rated as "non-certified level" buildings based on the above case development schedule, the first category could be used to improve all 10 case studies in four (4) stages respectively, from non-certified level to certified, silver, gold, and platinum levels.

As per the decided case development strategy, above features were applied respectively at each stage, to improve the conventional building with energy-efficient features in 4 stages as resembled in Table 3.6. Based on these features arrangement, all 10 cases of conventional buildings were improved stage by stage until the platinum level of energy efficiency is obtained. Therefore, the features listed here based on each stage will be applied at the respective stage hence, a case building will be developed from the current non-certified level to stage 4 platinum level in terms of energy efficiency.

3.10 Cost calculation for the newly adapted features of the energy-efficient building

Cost calculation of the newly adopted features was important since it gives an economic analysis as to how the costs and savings were varied. In calculating the cost attached to these developed buildings, the main framework was developed as in the figure below to guide the cost calculation by covering the whole scenario.

3.11 Construction cost variation at four (4) stages of energy-efficient office buildings

Each conventional office building was developed into a platinum-rated energy-efficient building in 4 stages. These new features contain a significant amount of initial cost. This cost is the main reason why the society/ the employees of the office buildings are reluctant to convert a building to an energy-efficient building. Therefore, the initial construction cost that is borne by these buildings at each stage of the development schedule was considered. Each building was analyzed separately as to how it varied from stage 1 certified level to stage 4 platinum level.

3.12 Cost-saving by energy-efficient features at four (4) stages of energy-efficient office buildings

Thereafter, it was analyzed as to how far newly included energy-efficient features have acted economically by assessing their performances. As the above figure depicts, the total cost saving was calculated. In considering water quantity saving, rainwater harvesting, wastewater treatment, and water-efficient fixtures had reduced the water cost positively by reusing the wastewater and rainwater, and reduction of water usage mainly. This water quantity saving reduces the energy needed for the pumping of water, but on the other hand, wastewater treatment plants accepted an energy cost while the rainwater harvesting system was designed as per the gravity flow technique. As additional water costs, water required for the irrigation purposes of green walls and roofs was considered. But it was considered as a portion of the treated wastewater. In considering indirect energy costs or savings, passive energy features which means features like building envelope, and orientation participate in the energy utilization of the building mainly due to the variations of the thermal comfort level. Therefore, to assess these passive energy features, DesignBuilder software was used to analyze the variation of the BEIs with changes in respective building features.

After the cost analysis was done, the changes in respective operational costs of the buildings and their reduction of annual expenses were analyzed and determined whether there was a considerable cost reduction in implementing those energy-efficient features.

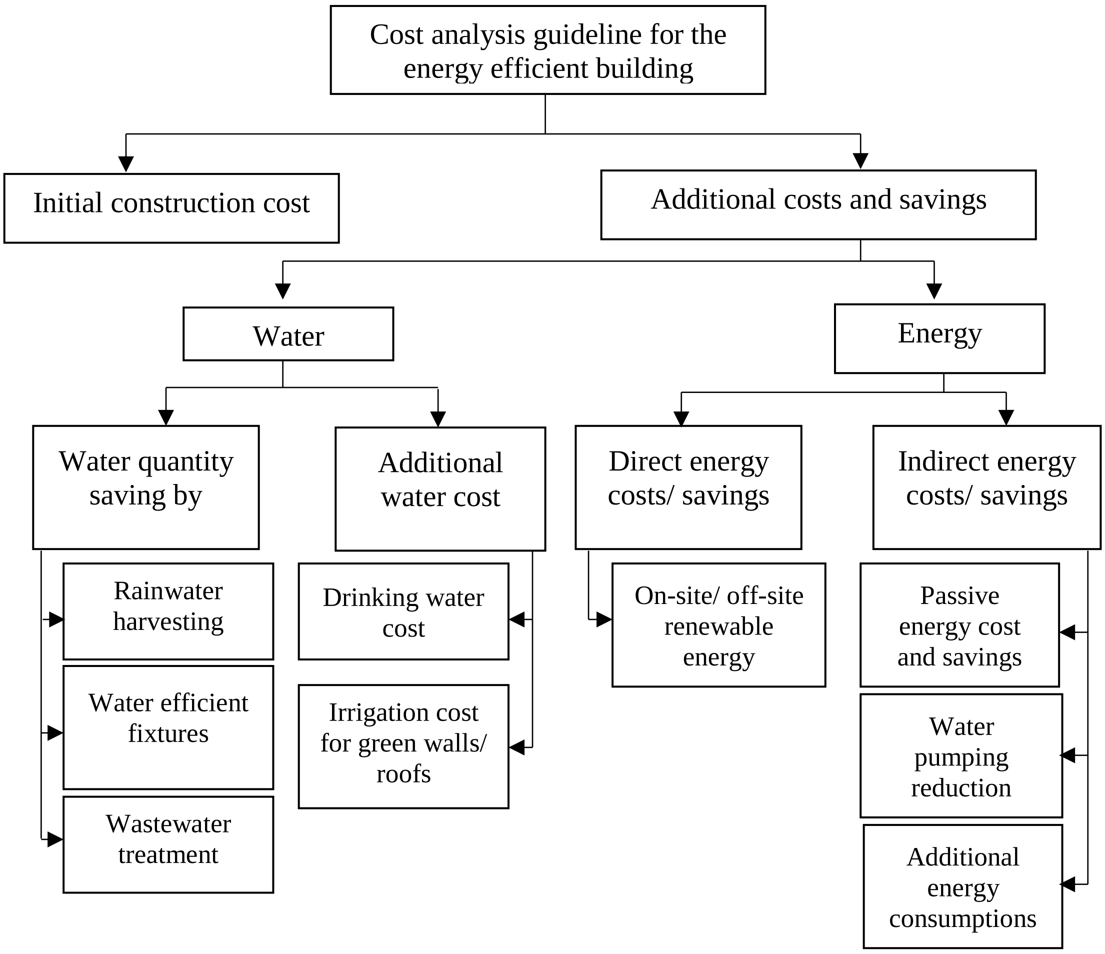


Figure 3.3: Cost analysis guideline for the energy efficient building

3.13 Payback periods at the four (4) stages of energy-efficient office buildings

After cost analyses of construction costs and the savings were done to each conventional office building and each development stage, the payback period was calculated simply by defining years which will take the relative energy efficient office building to recover the initial cost at every stage as shown in Equation 3.1. This result assisted the argument on which stage is the best stage for an office building to be converted to an energy-efficient office building from an economic perspective.

$$Payback\ period = \frac{Initial\ Investment}{Annual\ Payback} \quad \text{Equation 3.1}$$

3.14 Variation of the annual expenses of the best energy-efficient office building design

Upon the identification of the best design of the energy-efficient building to enter a conclusion, it needs to be further analyzed as to how they perform respectively. Therefore, identification of the variation of the annual expenses during a year is an important aspect. As a step forward in this study, annual expenses of the newly identified building design were measured and graphed to demarcate the differences in the expenses in a year.

3.15 Life Cycle Cost (LCC) calculation of the best energy-efficient office building design

Further, based on the above calculated, initial construction cost and annual savings, LCC was calculated to determine the economic performance of an energy-efficient office building from a life cycle perspective. This analysis further concluded as to which stage is the best stage for an average office building to economically perform with its best performances during the life cycle of the building. LCC was calculated as per equations 3 and 4 laid down above and subjected to the mentioned assumptions and the system boundary.

3.16 Summary

This chapter has presented the development of office buildings into energy-efficient buildings and identification of the performances. Mainly, the study conducted in order to identify the hurdles that the society is facing in their movement towards the sustainable construction. Building selection criteria was developed based on the walkthrough survey and the dispersion of the office buildings in Sri Lanka. Therefore, low-rise office buildings located in Comlombo city were considered and 10 case studies were selected for the study. These building were subject to LCC analysis and an energy simulation by using the DesignBuilder software version 6.0.

After this initial phase of the study, the selected buildings will be designed with energy-efficent features. In designing these case studies, $GREEN^{SL®}$ tool was used to invent a unique designing criteria. By using this tool, each building was designed as an energy-efficient building at 4 stages and then a cost analysis was done to identify the main initial additional costs that were gained at each stage. Following the analyses of construction costs, savings and payback periods the best low cost design was identified. In further assessing the design concluded so far, whole LCC was carried out to prove more whether that design is actually the best performing design with compared to the other stages and the conventional building.

4 PERFORMANCES OF DEVELOPED ENERGY-EFFICIENT OFFICE BUILDING DESIGNS

4.1 General

The results obtained during the process of the study were summarized and analyzed in this chapter to identify the variations in the performances of each case. The data analysis of such stages leads to the identification of the best design with the best energy-saving performances. During this chapter, various analysis was recognized such as LCC and BEI of existing buildings, construction costs derived for the installations of new energy-efficient features at 4 stages, and at last, performances of the new installations. This flow has opened the path to identifying the best design for office buildings.

4.2 Face-to-face interviews held with conventional office buildings

Following key suggestions were generated as one of the views of a part of the society, focusing on the importance and benefit of energy efficiency of an office building than that of a conventional building.

- Most office buildings are leased-out buildings and due to that, they do not tend to design the interior of the building as more energy-efficient.
- Electricity is the main mode of energy supplier of almost all the identified office buildings.
- When a decision was taken to select a building as the office space for their work in the future, they were concerned with various facts such as building location, building layout, reasonable/ lower monthly lease amount, interior condition, and so on but not energy efficiency of the building and not the saving that it provides.
- It was recognized that energy consumption (mainly electricity) of the building is mainly used for air conditioning for occupant comfort and lighting facilities of the interior.
- Not enough energy-saving techniques are practiced by the occupants of the buildings.

- There are no lighting or air conditioning schedules during an average of 8-10 working hours which function during the whole time.
- Occupants are not much familiar with the cost of the energy consumption of the building per month.
- They are aware of the higher cost that is attributed to energy-efficient technology installations and finds that it is not economically sound.

4.3 Employee perception of converting an existing office building into an energy-efficient building

25 challenges hindered the development of green buildings initially, as defined by the comprehensive literature review. The challenges were assessed to determine according to the Sri Lankan context. The 23 challenges were extracted from the EFA, "C08-immature green technology available in Sri Lanka" and "C25-it does not positively affect your business relationships" were eliminated as per the analysis. The variables were further compacted into four (4) main components in the PCA. It was observed that the Industry and Technology Environment (ITE) mostly caused a hinderance to the green building development in Sri Lanka. Even though the Green building concept has evolved by addressing the minimization of embodied energy, use of fewer resources like water, materials, and energy during its lifetime and also producing minimal waste or treating the waste, respondents believe that there are other corporate issues (CI) such as higher initial costs, longer payback period to recover the initial cost, potential damage to the existing building structure and construction cost which are directly impacting to their financial plans were causing them to move forward with converting their space to a green building. Stakeholder Awareness (SA) such as awareness of the community, clients, and professionals engaged in the construction industry was also believed to be vital in decision-making processes to construct/ convert buildings to energy-efficient green buildings. LCC of conventional office buildings

4.4 Life Cycle Cost (LCC) calculation of conventional office buildings

According to the below tables, a summary of LCC calculation results was represented. Table 4.1 shows the distribution of the costs among the other 4 stages of the life cycle which are, construction cost, energy cost, water cost, and maintenance cost, and the LCC was given. However, an average LCC value for a conventional office building in Sri Lanka, mainly being the region of Colombo, is set around 162,559.00LKR.

Table 4.1: LCC of conventional office buildings

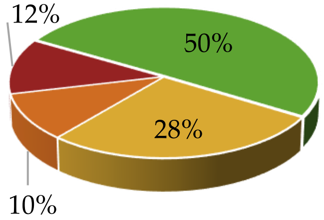
	Construction (LKR)	Energy (LKR)	Water (LKR)	O&M (LKR)	Total LCC (LKR/m^2)
Case 1	65,638,515.42	35,943,966.68	13,231,165.01	15,642,628.67	205,119.93
Case 2	63,513,989.08	22,590,665.34	15,273,833.26	11,167,298.85	141,034.82
Case 3	170,035,795.43	125,563,927.41	3,101,241.21	7,044,437.98	160,833.98
Case 4	208,796,519.40	122,221,252.65	6,272,451.88	105,350,566.76	145,797.36
Case 5	388,251,589.50	193,339,661.55	27,583,125.05	98,818,049.24	138,686.08
Case 6	132,000,000.00	71,750,496.62	26,461,755.01	31,278,060.80	204,289.31
Case 7	140,000,000.00	73,039,427.70	8,163,230.15	85,928,738.47	146,253.05
Case 8	64,000,000.00	26,423,087.08	16,756,104.00	13,963,420.00	143,364.04
Case 9	250,000,000.00	122,448,452.32	19,355,448.34	73,039,427.70	166,015.47
Case 10	140,000,000.00	89,652,159.60	4,296,436.92	6,444,655.39	174,198.01

In Table 4.3 below a graphical representation of the distribution of LCC cost was presented. According to this, it is noted that nearly 50% of the LCC of an office building was assigned to the initial construction cost. Secondly, the biggest cost was the energy utilization of the building. When we consider operational costs only and neglected the construction cost for a moment, then it was recognized that the highest cost was energy consumption cost.

Table 4.2: Energy utilization costs during the life cycle of an office building

	Energy cost fraction of LCC
Case 1	28%
Case 2	20%
Case 3	41%
Case 4	28%
Case 5	27%
Case 6	27%
Case 7	24%
Case 8	22%
Case 9	26%
Case 10	37%

Table 4.3: LCC of conventional office buildings variation

<table>
<tr><td>Case 1</td><td>Case 2</td><td>Case 3</td><td>Case 4</td><td>Case 5</td></tr>
<tr>
<td>
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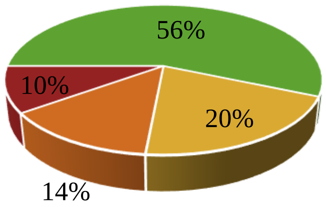
<td>
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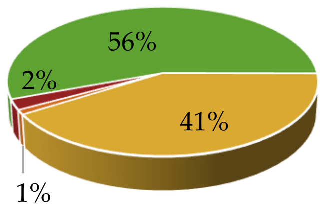
<td>
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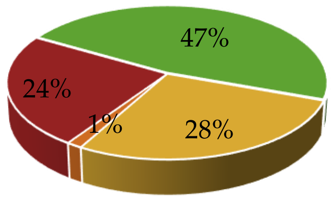
<td>
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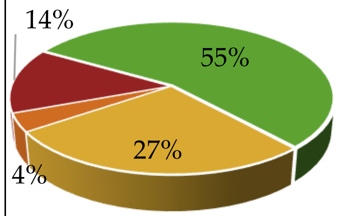
<td>
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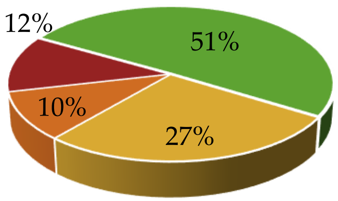
<tr><td>Case 6</td><td>Case 7</td><td>Case 8</td><td>Case 9</td><td>Case 10</td></tr>
<tr>
<td>
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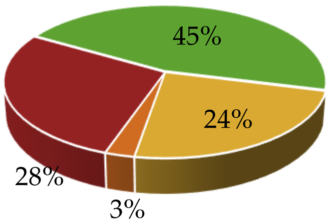
<td>
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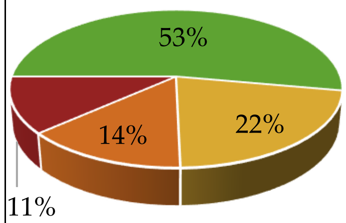
<td>
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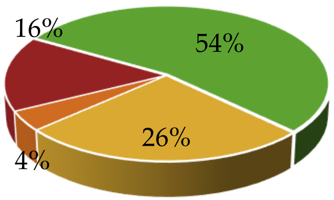
<td>
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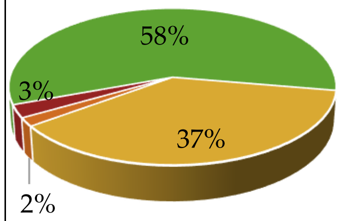
<td>
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Construction Cost   Energy Cost   Maintenance Cost   Water Cost

The above Table 4.2 summarizes the fraction that is contributed to energy cost within the life cycle of an office building, which was around 20-30% of the LCC of the building. It means that a portion of 1/5 of the whole costs borne by the building has been dedicated to energy utilization. Therefore, it proves a point that the energy efficiency of an office building is an important factor to be concerned with not only environmentally, but economically too.

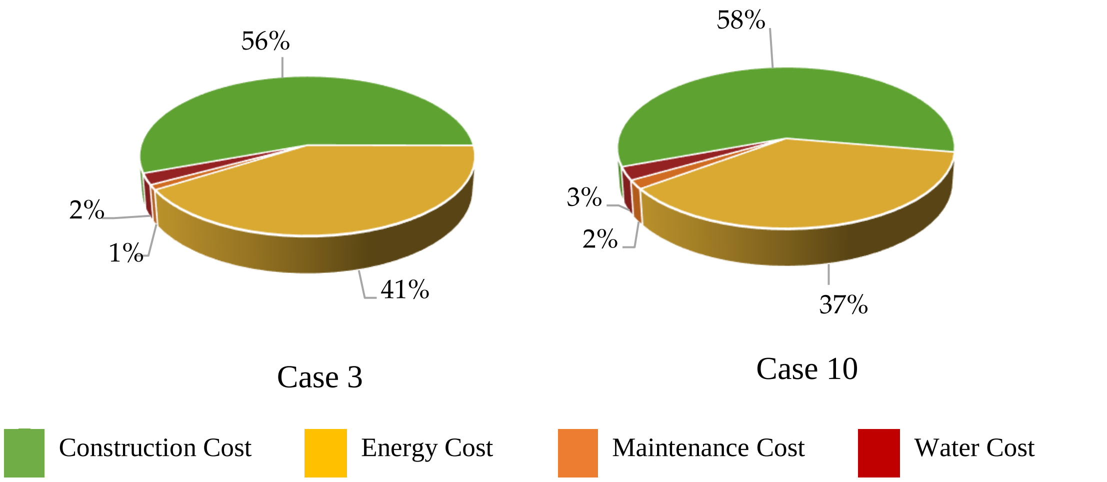


Figure 4.1: Type I variation from the general distribution of LCC

Referring back to Table 4.3 it was recognized that there were 2 types of variations among all the 10 cases on the general distribution of LCC.

Figure 4.1 replicates the Type I variation of LCC distribution from the general distribution of the LCC of other buildings. This variation was showing a higher energy utilization of more than 35% and the general distribution of energy cost was between 20-30%. For this variation to occur the reason was identified as increased energy consumption of these 2 buildings and it was due to their functioning as IT firms. Higher energy utilization can be expected from such type of building functions due to its heavy usage of electronic devices like laptops, printers, etc. throughout the day.

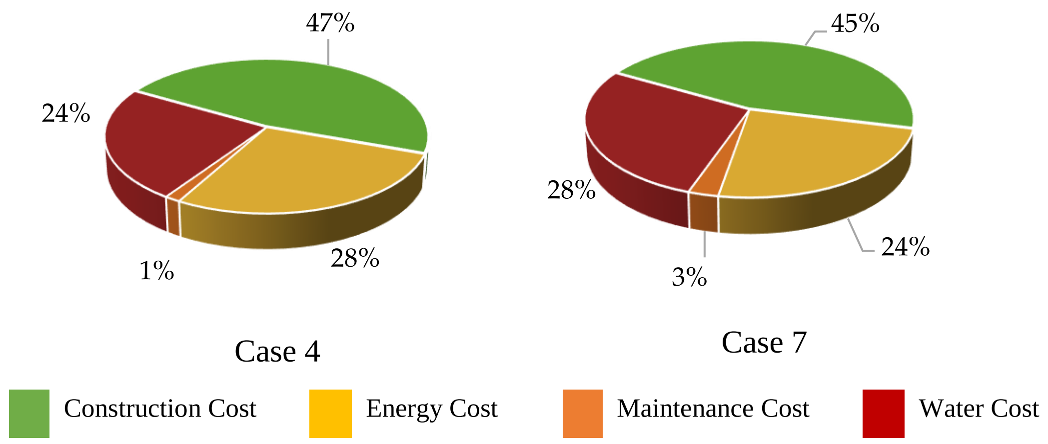


Figure 4.2: Type II variation from the general distribution of LCC

Type II variation as shown in Figure 4.2 was identified as it bears a higher cost for water throughout the life cycle of the building. Nevertheless, these 2 buildings were the oldest in our case studies, which were constructed in the years 2000 and 2002 respectively. Therefore, this high cost for water was identified as the lack of water-saving techniques, appliances, and lower maintenance have resulted in the high cost for water in this LCC.

4.5 Energy simulation of conventional office buildings

Energy simulation of the selected conventional office buildings was done by DesignBuilder software version 6.0 based on the data gathered from site inspections, observations, and data collected from the building staff and building owners. The building construction and operational data were needed to derive the BEI and the building model from the software. DesignBuilder manual was used for the proper modeling of the buildings (DesignBuilder Software, 2009).

After drawing the models of the conventional buildings, BEI was simulated which resulted in the energy consumption in kilowatt-hours per gross area, per annum. Following Table 4.5 shows the BEIs resulting from the DesignBuilder software. These results elaborate that the BEI of a general conventional office building varies between 200–300 kWh/m^2/a. Table 4.4 shows the modeled conventional buildings and their designs derived from the software.

Table 4.4: Modeled conventional buildings using the DesignBuilder software

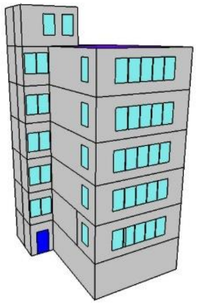
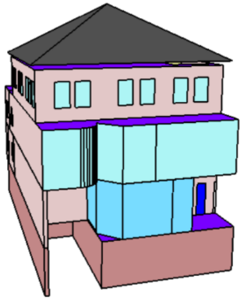
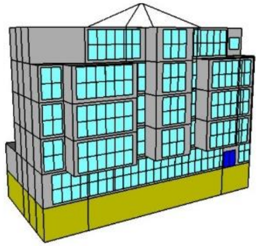
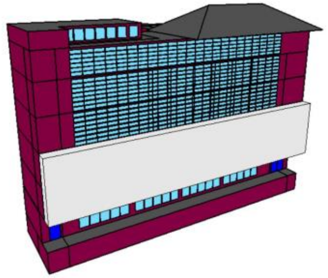
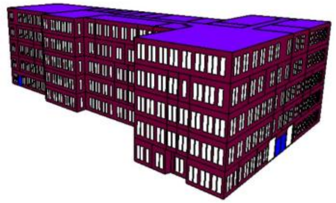
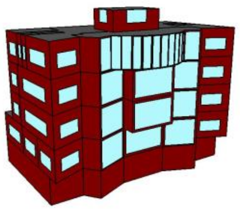
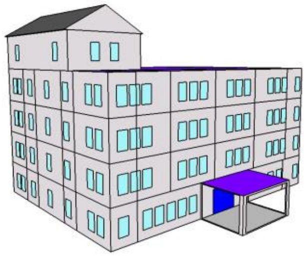
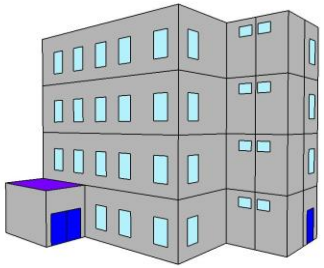
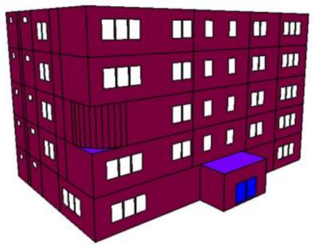
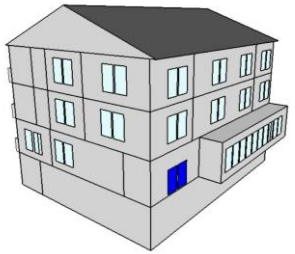
Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
				
337.29 kWh/m^2	210.99 kWh/m^2	382.57 kWh/m^2	207.09 kWh/m^2	231.53 kWh/m^2
Case 6	**Case 7**	**Case 8**	**Case 9**	**Case 10**
				
245.25 kWh/m^2	260.00 kWh/ m^2	210.14 kWh/ m^2	249.97 kWh/ m^2	239.64 kWh/ m^2

Table 4.5: BEI values of the conventional building cases

	BEI
Case 1	337.29 kWh/m^2
Case 2	210.99 kWh/m^2
Case 3	382.57 kWh/m^2
Case 4	207.09 kWh/m^2
Case 5	231.53 kWh/m^2
Case 6	245.25 kWh/m^2
Case 7	260.00 kWh/ m^2
Case 8	210.14 kWh/ m^2
Case 9	249.97 kWh/ m^2
Case 10	239.64 kWh/ m^2

4.6 Assessing the current green building state of conventional office buildings

The selected conventional office buildings were assessed using the GREEN$^{SL®}$ tool developed by the GBCSL. Based on the points criteria, each aspect was assessed and points were allocated. As a result, all the buildings were identified as in the non-certified level of the GREEN$^{SL®}$ tool by obtaining between 20-30 points. It was recognized that to consider a building green building the minimal point that needs to be achieved is 40 points, hence certified level can be obtained.

Table 4.6: Summary of the current green ratings of conventional office buildings

	Current status	Points achieved
Case 1	Non-certified level	23
Case 2	Non-certified level	28
Case 3	Non-certified level	24
Case 4	Non-certified level	30
Case 5	Non-certified level	29
Case 6	Non-certified level	24
Case 7	Non-certified level	28
Case 8	Non-certified level	23
Case 9	Non-certified level	24
Case 10	Non-certified level	27

Table 4.6 above shows the summary of points all 10 case studies achieved during the rating of the buildings. Based on this non-certified level a case development schedule

was selected hence all these building cases were developed in four stages to reach the platinum level energy efficiency for the building.

4.7 Construction cost variation at four (4) stages of energy-efficient office buildings

According to the cost analysis done for the newly adopted energy-efficient features, it was inevitable that there is an attractive cost for each feature at the installation stage of it. Since society is of the view that this initial cost is the main barrier for them to moving toward energy-efficient buildings, it is important to assess how this initial cost varies with the stages of energy efficiency.

Table 4.7: Variation of construction cost with stages of energy efficiency

	Stage 1	**Stage 2**	**Stage 3**	**Stage 4**
Case 1	09.27%	18.82%	31.95%	33.01%
Case 2	14.01%	19.21%	27.25%	28.48%
Case 3	23.37%	50.23%	77.96%	80.40%
Case 4	09.44%	19.64%	32.96%	34.83%
Case 5	20.06%	40.34%	58.13%	59.59%
Case 6	13.89%	23.83%	31.89%	35.23%
Case 7	29.78%	41.43%	58.34%	64.75%
Case 8	16.89%	23.87%	34.36%	39.14%
Case 9	20.85%	26.94%	37.12%	41.78%
Case 10	21.45%	29.68%	42.77%	49.83%

The above Table 4.7 illustrates the variation of the construction cost that had to be born at the adoption of new energy-efficient features as a percentage of increase from the initial construction cost of the conventional building. Simply it refers to the percentage of increase at each stage with the improvements done additionally.

Moreover, below Table 4.8 is the graphical representation of the increase in initial costs of the new features with each stage from stage 1: certified level to stage 4: platinum level. Therefore, it replicates that the highest cost was borne by the stage 4 level with an average increase of 40-50% from the construction cost of the conventional building with no considerable energy efficiency noticed. On the other hand, the minimum cost was borne at stage 1 with the minimum of energy-efficient features installed.

4.8 Cost-saving by energy-efficient features at four (4) stages of energy-efficient office buildings

In assessing the best design for an office building it is needed to see the benefits attached to the new implementations too. Based on the cost calculation guideline described in the above Figure 3.3, the resulted annual savings or additional costs were calculated to identify the best stage that can be reached as the optimum design for an office building to convert or construct newly as an energy-efficient building. The annual savings resulting from these features were shown in Table 4.9.

As illustrated in Table 4.9 below annual savings resulting from the energy saving due to the installation of the energy-efficient features were positively increased from stage 1 to stage 4. The results were gained in millions per year as a cumulative saving from energy and water. According to these results, it can be seen that stage 1 achieved the lowest annual saving compared to the other stages. Stage 4 had gained the maximum annual savings as a result of the installation of the best energy-saving features. Even though, stage 4 acquired the highest initial construction cost over all other stages the annual savings were also the highest at stage 4 which is a positive remark in considering stage 4 as a better approach than other stages. However, it is important to further assess how long will it take to recover this initial cost at these stages.

Table 4.8: Construction cost variation at 4 stages of energy-efficient office buildings

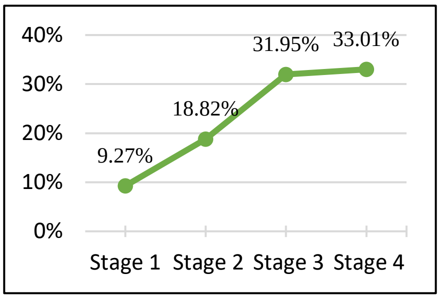
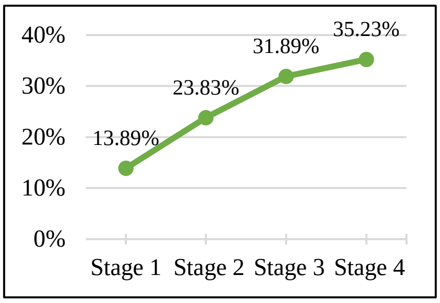
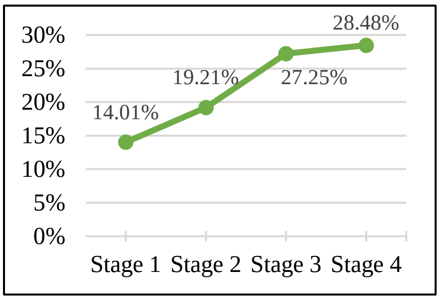
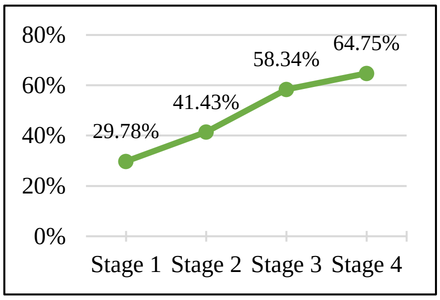
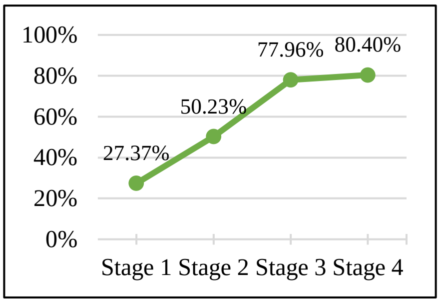
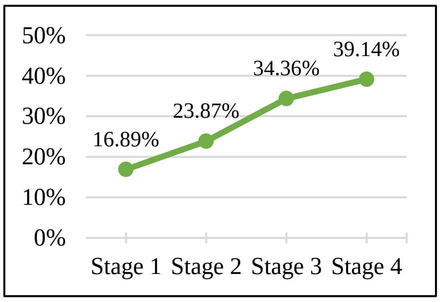
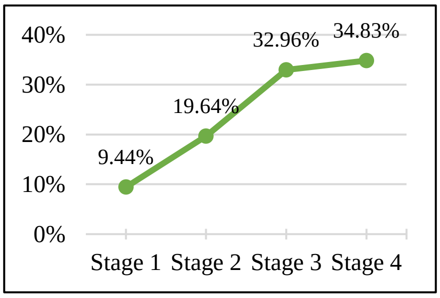
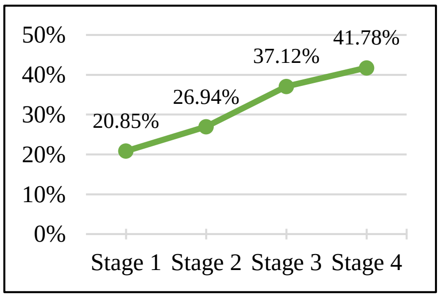
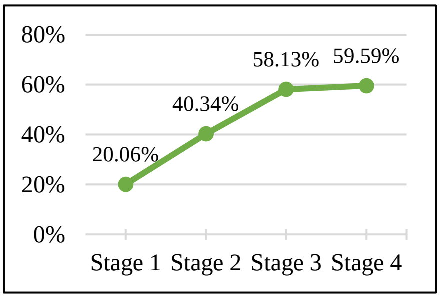
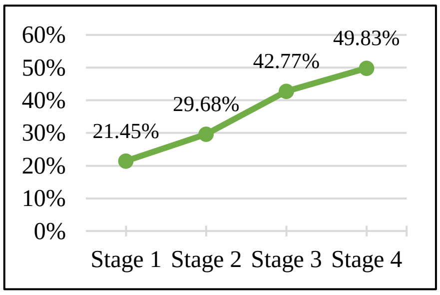
Case 1		Case 6	
Case 2		Case 7	
Case 3		Case 8	
Case 4		Case 9	
Case 5		Case 10	

Table 4.9: Annual cost savings at 4 stages of energy-efficient office buildings (in millions)

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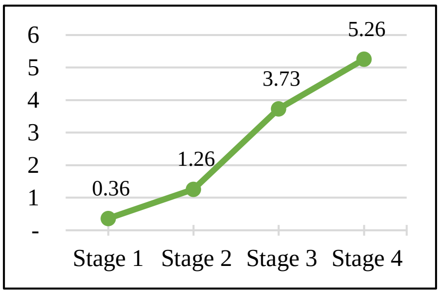
<td>
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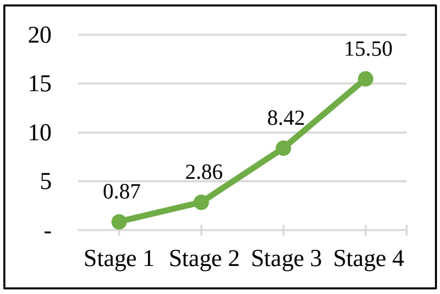
<td>
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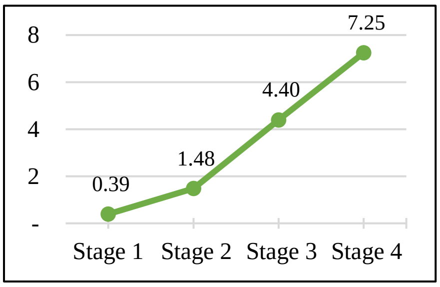
<td>
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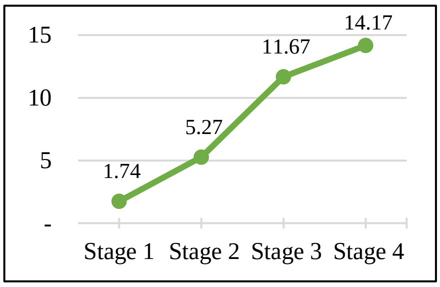
<td>
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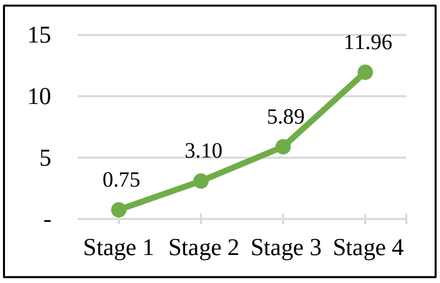
<td>
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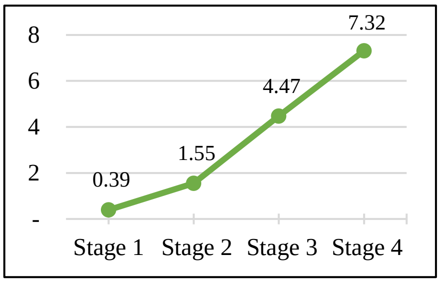
<td>
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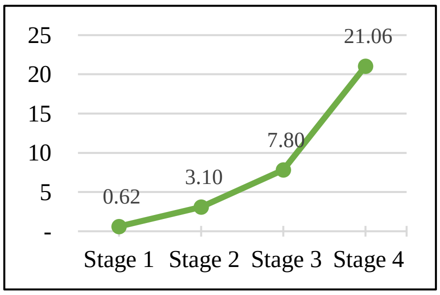
<td>
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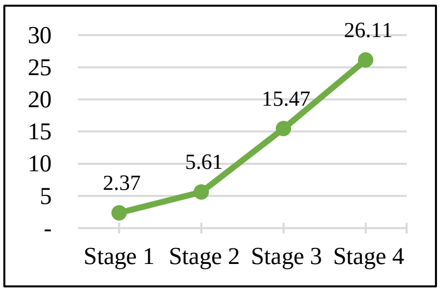
<td>
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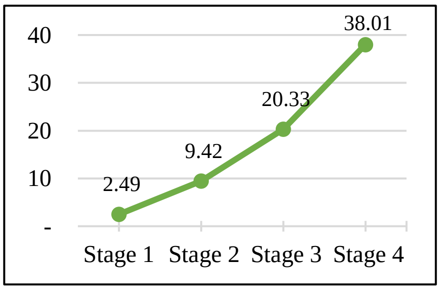
<td>
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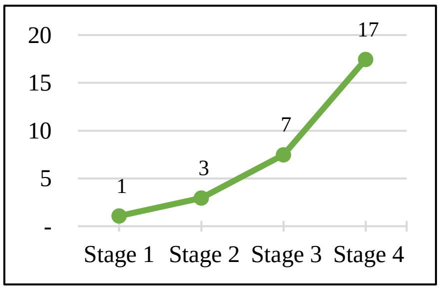
<td>
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4.9 Payback periods at the four (4) stages of energy-efficient office buildings

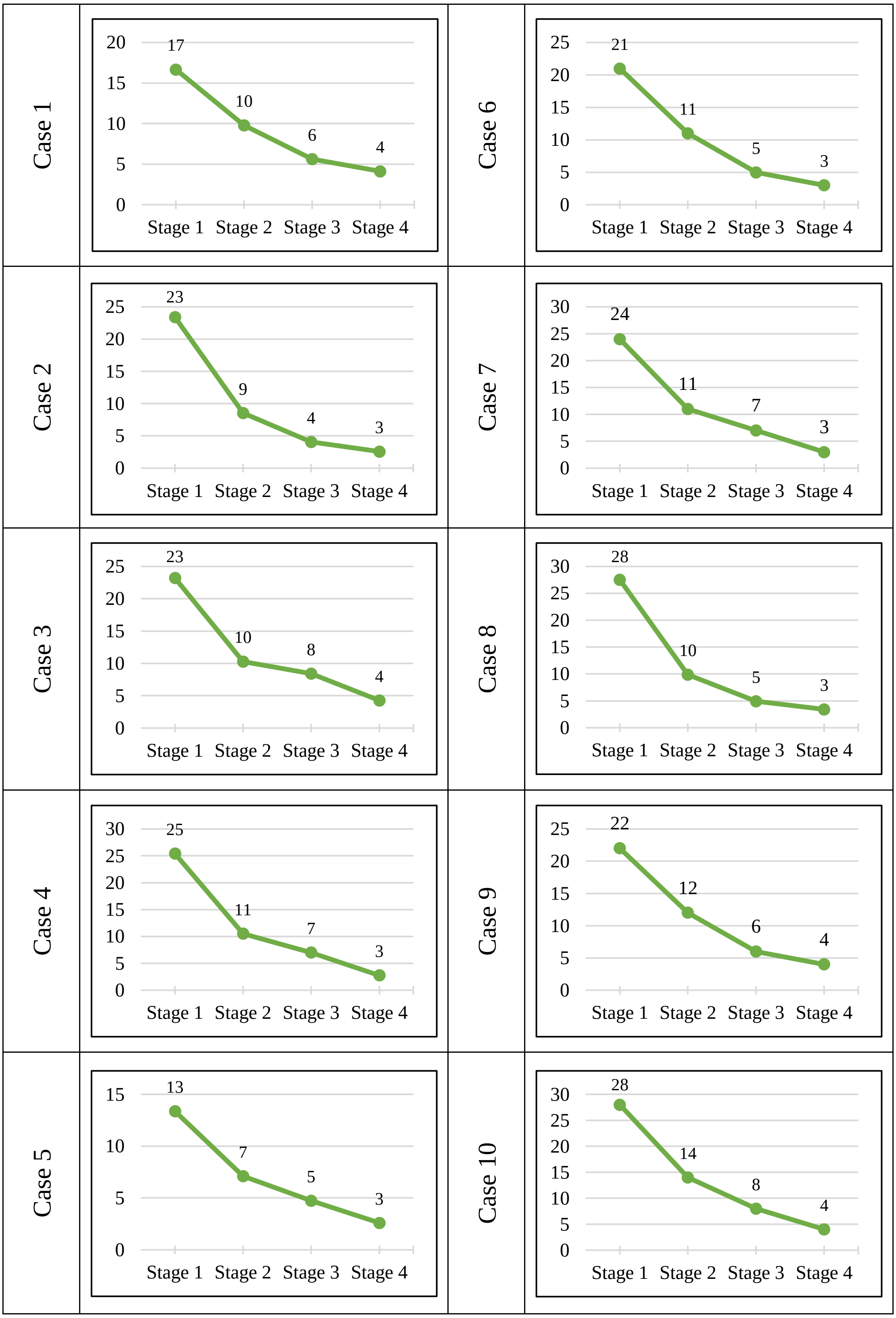
The payback period is the time required for a project to recover the initial cost of a project. Hence, in considering whether such a project is economically feasible it is essential to focus on the project from a life cycle perspective. the shorter the time takes to recover the initial cost, the better that project sounds economical.

Table 4.10: Payback periods at the 4 stages of energy-efficient office buildings (in years)

	Stage 1	Stage 2	Stage 3	Stage 4
Case 1	17	10	6	4
Case 2	23	9	4	3
Case 3	23	10	8	4
Case 4	25	11	7	3
Case 5	13	7	5	3
Case 6	21	11	5	3
Case 7	24	11	7	3
Case 8	28	10	5	3
Case 9	22	12	6	4
Case 10	28	14	9	4

Table 4.10 and Table 4.11 depict how the payback period has varied from stage 1 to stage 4. According to these results, it was recognized that stage 4 has achieved the lowest payback period which was around 3-4 years over the other stages. Furthermore, 3-4 years is a considerably lower period to recover the initial cost of a building which consists of an average lifetime of 50 years. In other words, after recovering the initial cost within 3-4 years, a rest period of 47 years becomes a profit to the building yearly from these energy-efficient features. Hence, it is further accepted that the stage 4 design of an office building with related energy-efficient features is likely to be a better design compared to the other stages.

Table 4.11: Variation of payback period at 4 stages of energy-efficient office buildings (in years)



4.10 Variation of the annual operating expenses of stage 4: platinum rated energy efficient office buildings

Variation of annual operating expenses is a step forward to assess the expenses and savings that were born by the best design identified so far, stage 4. Before concluding the best design of the building, the variation of the operational expenses was considered separately.

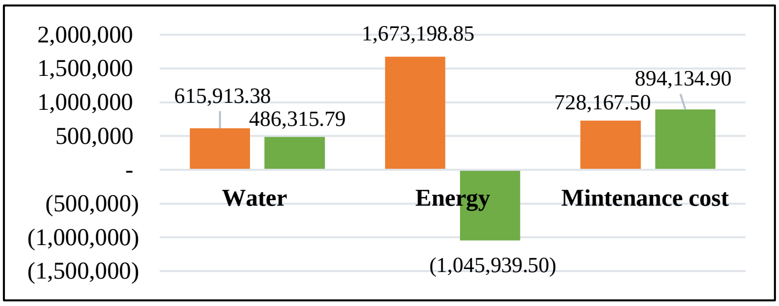
As per these graphical illustrations in Table 4.12, it was recognized that the annual energy cost has been reduced critically by the installation of these energy-efficient features. Also, water costs have been reduced due to the reuse of water for non-potable uses, and for potable uses drinking water was purchased. Apart from these 2 savings, the maintenance cost had been increased by a considerable amount since the additional cost for the maintenance of the new features was accumulated to the already available costs.

In addressing the variation of the maintenance costs, Figure 4.3 reflects the additional amount that had to be borne by the owner for the maintenance of the building. An average, 30-40% increase in annual maintenance cost was witnessed due to these additional new features.

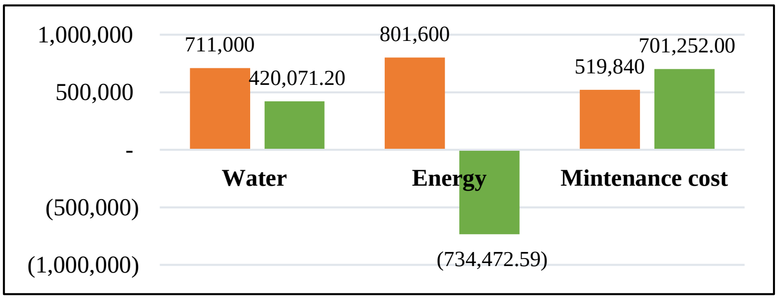
The variation of the annual maintenance cost per gross floor area of all the 10 cases of, stage 4 platinum-rated energy-efficient buildings was shown in Figure 4.3 below. In this figure, a comparison between the maintenance cost of the conventional building and the new energy-efficient building was reflected.

Table 4.12: Variation of the annual operating expenses of stage 4 platinum-rated energy-efficient office buildings (in LKR)

Case 1



Case 2



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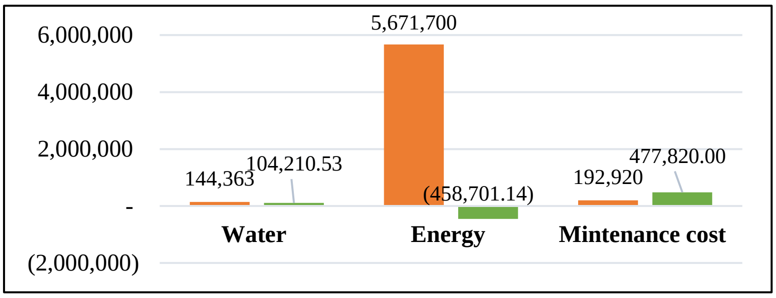
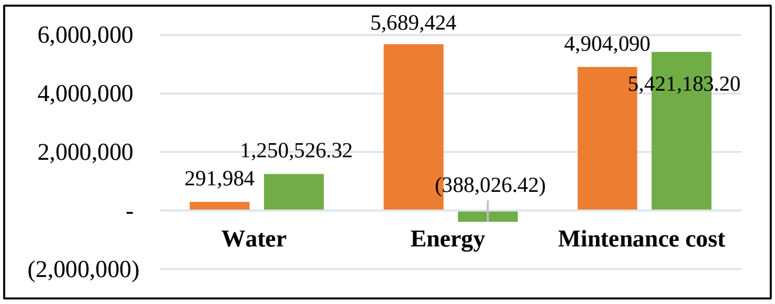


Case 4



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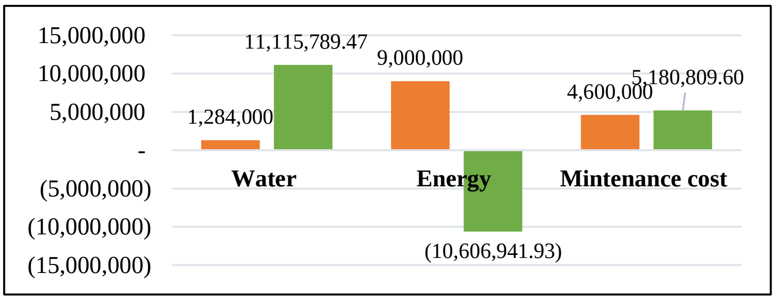
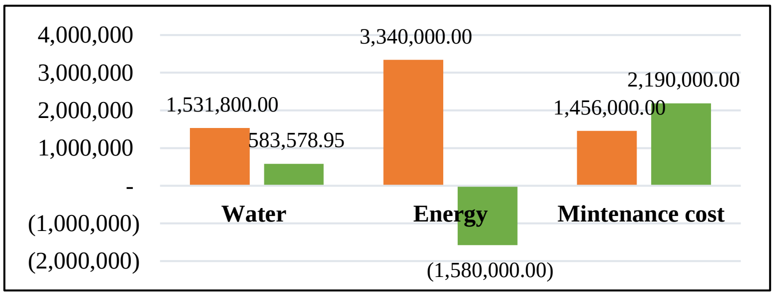


Case 6



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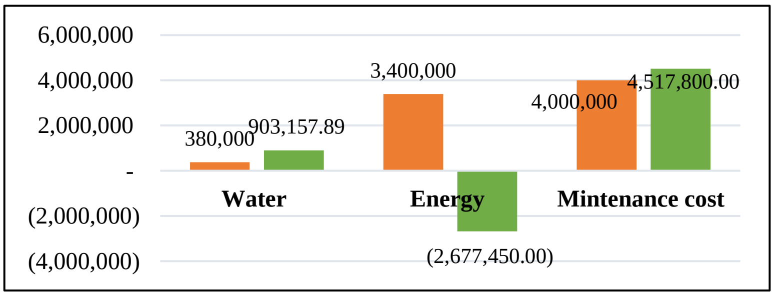

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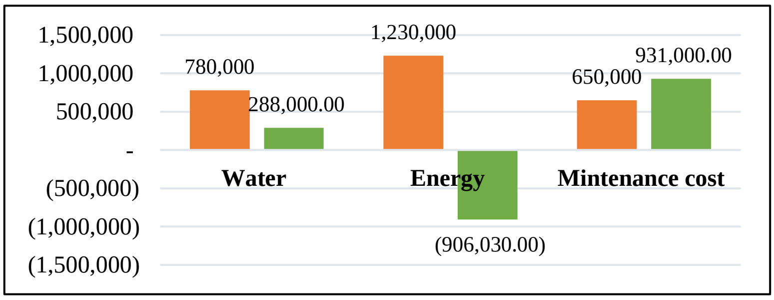

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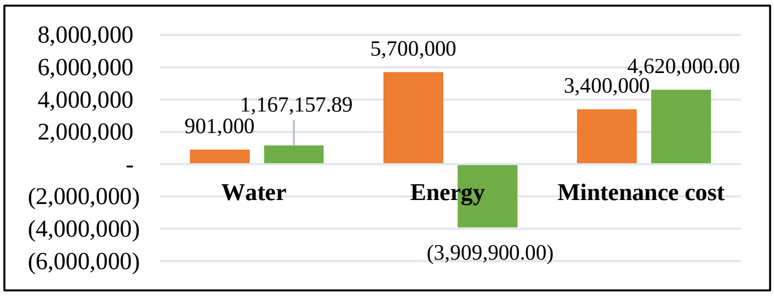
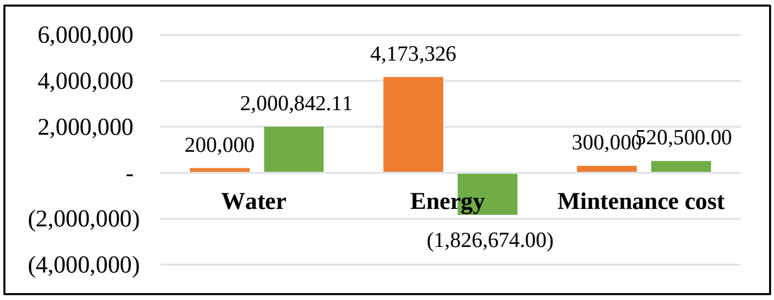


Case 10



Annual Expenses in Conventional Office Building (LKR)

Annual Expenses in stage 4 Platinum level Energy efficient Office Building (LKR)

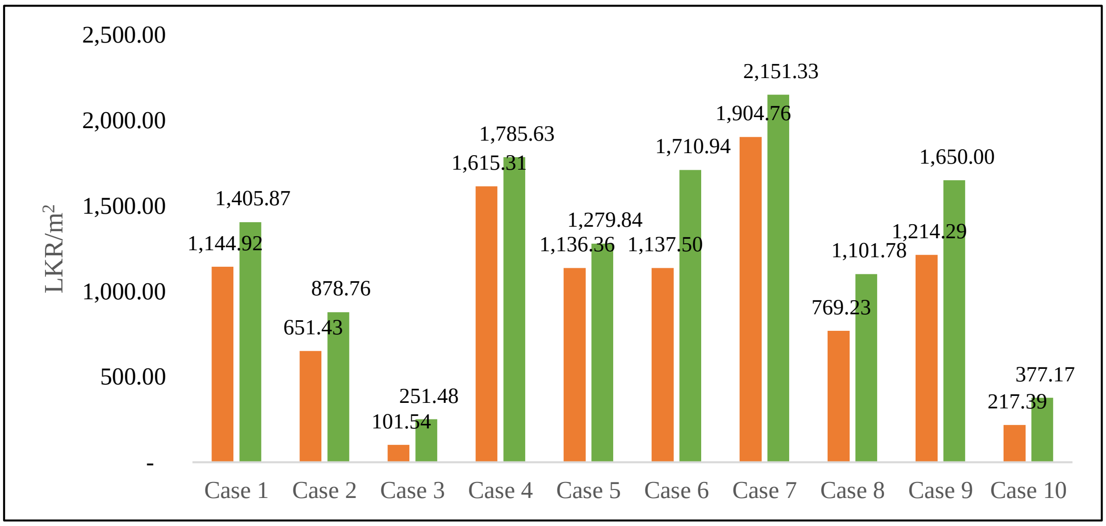


Figure 4.3: Variation of the annual maintenance cost of the conventional building vs. stage 4: platinum rated energy efficient office buildings (in LKR/m^2)

4.11 Life Cycle Cost (LCC) calculation of stage 4: platinum rated energy efficient office buildings

As the final step before the conclusion of the best energy-efficient design, it is necessary to look from the life cycle perspective. in assessing the LCC calculation new expenses and savings were considered to analyze the new total cost for the newly designed building for a lifetime of 50 years. This calculation was also subjected to the defined system boundary and the assumptions. Table 4.13 shows the tabular form of the analyzed LCC results and the table shows the graphical representation of the LCC variation from conventional buildings to the stage 4 platinum rated energy efficient building as in LKR per gross floor area (LKR/m^2).

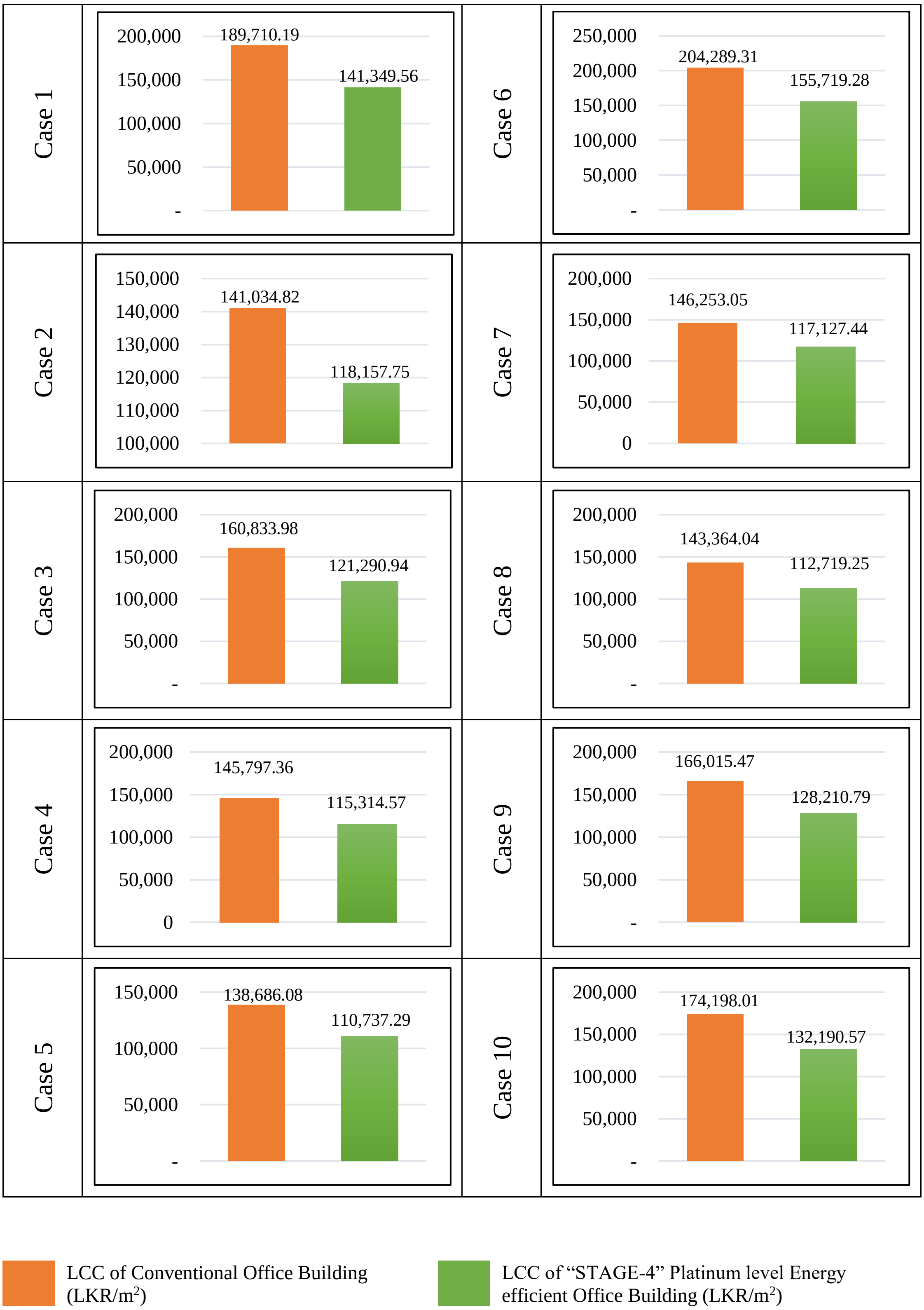
According to Table 4.14, a clear reduction of LCC was seen at stage 4 of the energy-efficient building design compared to the conventional office building of the same case. An average reduction of LCC was calculated as between 20-25% of reduction with its conventional building's LCC. It is a considerable value attracted from considering only the energy efficiency of the building based on the GREEN$^{SL®}$ rating tool of GBCSL.

Table 4.13: Variation of LCC between conventional office building vs. stage 4: platinum rated energy efficient office buildings

	LCC in conventional buildings (LKR/m^2)	LCC in stage 4 energy efficient building design (LKR/m^2)	Reduction/ Excess	The difference as a percentage (%)
Case 1	205,119.93	141,349.56	Reduction	25.49%
Case 2	141,034.82	118,157.75	Reduction	16.22%
Case 3	160,833.98	120,290.94	Reduction	24.59%
Case 4	145,797.36	115,314.57	Reduction	20.91%
Case 5	138,686.08	110,737.29	Reduction	20.15%
Case 6	204,289.31	155,719.28	Reduction	23.78%
Case 7	146,253.05	117,127.44	Reduction	19.91%
Case 8	143,364.04	112,719.25	Reduction	21.38%
Case 9	166,015.47	128,210.79	Reduction	22.77%
Case 10	174,198.01	132,190.57	Reduction	24.11%

Every stage 4 energy-efficient building showed a clear reduction of the LCC. Therefore, the importance of assessing a building not solely based on the initial construction cost, but on the life, cycle perspective can be seen evidently.

Table 4.14: Variation of LCC between conventional office buildings Vs. stage 4: platinum rated energy efficient office buildings (LKR/m^2)



4.12 Summary

This chapter provided the results and analyses obtained during the study and convince that the best energy-efficient office building design can be identified based on the results provided. According to the deviation of the life cycle cost of the energy-efficient building from its conventional building, it is understood that the lowest LCC bears at the stage 4 building with the best performing energy-efficient features. By analyzing all the data obtained, it was understood that the best design can be finalized with the best environmentally sound performances.

The average BEI of a typical office building located in the city of Colombo, Sri Lanka is identified to be around 200 – 300 $kWh/m^2/a$ while LCC is around 162,559.00 LKR as an average, subject to the defined system boundary. Within this LCC of the buildings, 20-30% had been allocated for the energy consumption costs of the buildings, which resembles that energy is a major costly service of a building during its operational stage.

Based on the development schedule the building cases were developed in 4 stages. Analyses done for these developments have resulted that, the lowest initial construction cost was borne by stage 1 while the highest cost was at stage 4. The initial construction cost increment is around 30-50% of the construction cost of conventional buildings. However, compared to the performances of the newly incorporated energy-efficient features stage 4 was resulting in a maximum annual profit than other stages subject to their building performances.

The payback period of a 3-4 years period has resulted in the least cost recovery period for stage 4 of the building. Hence, it concludes that even though stage 4 bears the maximum cost for the energy-efficient features, the cost can be recovered within 3-4 years while stage 1 needs more than 15 years for the same.

In assessing the life cycle perspective of these buildings, it has been observed that the LCC of stage 4 energy-efficient buildings has been reduced by 20-25%. Moreover, the maintenance cost of the stage 4 design resulted to be increased by 30-40% as an additional cost attributed due to the energy-efficient features.

So, all analyses presented in this chapter conclude that stage 4 platinum-rated building design is the best low-cost building design with sustainable features for an office building in Sri Lanka.

5 CONCLUSIONS

5.1 Conclusions and recommendations

- Based on the literature, office building sector was identified as one of the major consumer of energy during the operational stage of the building (Cidell, 2009). 30% of operational costs have been attributed just for the energy utilization of the building.
- In analyzing the office employees on converting their office building to an energy-efficient building, the main key barrier identified during the face-to-face interviews and online surveys were the high initial cost associated with the energy efficient features during their installation or the construction, fewer savings than what really expected and hence results in long payback periods. These two factors mainly resemble the lack of proper knowledge of the society on the green measures and energy efficient measures available. Therefore, the need for proper economic analysis should be done especially from the Sri Lankan perspective on how these energy efficient measures bear a high initial cost, how these measures result in an annual saving to the building, and what will be the payback period.
- To encourage the office employees and office building owners to move towards green buildings or energy-efficient buildings, it is important to be aware of how energy-efficient buildings perform. So, having knowledgeable personnel in decision-making is more important to see an uprising trend of energy-efficient green buildings.
- In analyzing conventional buildings, the BEI of conventional office buildings is around 250kWh/m^2/annum as an average value. Moreover, LCC was a major part of the study subject to the system boundary that was preliminary defined. A modern design type conventional office building is generally having an LCC ranging between 140,000 LKR/m^2 to 200,000 LKR/m^2 subject to an inflation rate of 4% which is Sri Lanka's average inflation rate before the year 2020.

  As a future work for this analysis, conducting the LCC of these buildings not limiting to a defined system boundary and conducting a whole LCC would be ideal to have a bigger picture and a complete view of the performances of the buildings.

- When considering the LCC of a conventional office building, includes construction cost, energy, water, and maintenance costs of the building. As per the 10 case studies analyzed, within the dispersion of costs, construction cost bears nearly 50% of the whole life cycle cost of an office building. Secondly, energy cost is the main cost of the building having a portion of an average of 20% - 30% of LCC. Other respective costs are water cost and maintenance cost. They vary based on each building's performance and maintenance.
- Concerning the operational stage of the building, energy is the prominant cost that has to be borne by the organization. Hence, energy efficiency must be one crucial factor to be considered irrespective of spending an unnecessary amount of money on energy consumption.
- In designing an energy-efficient building subject to the defined development criteria of the study, stage 4 platinum level energy efficient building was identified as the highest initial construction cost-bearing building. It was having an additional 30%-50% incremental construction cost from its base conventional building construction cost. On the other hand, concerning annual savings resulting from the adopted energy efficient features the highest annual savings resulted at the stage 4 building design. Finally, the payback period was least at the stage 4 platinum level energy-efficient building owing to 3-4 years to recover the initial cost, while stage 1 building has a payback period of 15-25 years as an average.
- Therefore, the best low-cost energy efficient design can be concluded as the stage 4 platinum level energy efficient office building design having the lowest payback period with the highest annual savings from energy efficiency, even though it bears the highest initial cost.
- According to the variation of the annual expenses of stage 4 buildings, they bear a lower cost for energy and a higher cost for maintenance compared to their respective conventional buildings. The maintenance cost of the energy-efficient building has been raised by 30% to 40% on average because of the newly adopted energy-efficient features maintenance.

- Consequently, the LCC results of the stage 4 platinum level energy efficient building resembles a 20% to 25% LCC cost reduction compared to their respective conventional building.
- Hence, it furthermore concludes that stage 4 building design is the best low-cost energy-efficient design. Therefore, even though, this building design bears the highest initial cost for the energy-efficient features, the most economically sound investment is the stage 4 office building design from a life cycle perspective.

5.2 Future work

- To conduct a wide approach of survey in identifying more hurdles attached with the society in achieving sustainable or energy-efficient constructions. Therefore, as a future work, this survey can be initiated and further researches can be initated in addressing the misconcepts the society is bearing about the green buildings.
- To identify the LCC performance of energy-efficient features developed based on the same designing criteria for the commercial building sector in Sri Lanka can be suggested since, it is a growing sector of buildings in Sri Lanka.

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APPENDIX A

What Hinders Converting Your Existing Office Building to an Green Building?

* Required

1. How would you describe the work you do (designation)? *

Mark only one oval.

- Director and above
- General Manager
- Manager
- Executive
- Personal Assistant
- Secretary
- Technician
- Clerk
- Intern
- Engineer

2. What is your gender? *

Mark only one oval.

- Male
- Female

3. What is your age category? *

Mark only one oval.

- ◯ 18-20
- ◯ 21-30
- ◯ 31-40
- ◯ 41-50
- ◯ Over 50

4. What is your level of education? *

Mark only one oval.

- ◯ Primary education
- ◯ Higher education
- ◯ Bachelor Degree
- ◯ Postgraduate

5. Your office falls under *

Mark only one oval.

- ◯ Public Sector
- ◯ Private Sector
- ◯ Semi-Government
- ◯ NGO
- ◯ Other

6. Where does your office locate at? *

Mark only one oval.

- Ampara
- Anuradhapura
- Badulla
- Batticloa
- Colombo
- Galle
- Gampaha
- Hambanthota
- Jaffna
- Kalutara
- Kandy
- Kegalle
- Kilinochchi
- Kurunegala
- Mannar
- Matale
- Matara
- Mulathivu
- Monaragala
- Nuwara Eliya
- Polonnaruwa
- Puttalam
- Rathnapura
- Trinco
- Wavuniya

7. "What stops you from converting your office building into a green building? Rate your opinion from following reasons"(1= Strongly disagree 2= Disagree 3= Neutral 4= Agree 5= Strongly agree) *

Mark only one oval per row.

	1 Strongly disagree	2 Disagree	3 Neutral	4 Agree	5 Strongly agree
Lack of regulations and policy for green buildings					
Lack of industrial guidance					
Lack of effective green building development modes					
Lack of effective supervision from government					
Inadequate support from related green building institutions					
Increment of construction cost					
Potential damage to the existing building structure					
Immature green technology available in Sri Lanka					
Higher initial cost					
Lack of financial support					

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Immature green material market					
Public concerns on quality of green materials					
Lack of environmental awareness of the contractor/client					
Lack of environmental awareness of engaged professionals					
Lack of environmental awareness of community					
Low demand for green buildings					
Lack of trainings in green building construction					
Lack of publicity for green buildings					
Limited benefit to enterprise reputation					
Clients do not seek for the green rating to do business					
Longer payback period to recover the initial cost					
Lack of professionals					

attached for the energy management of the building					
Issues based on building ownership (Ex: Your office building is a rented space, not an own premises by your company/ organization)	⬭	⬭	⬭	⬭	⬭
No potential benefits are foreseen	⬭	⬭	⬭	⬭	⬭
It does not positively affect your business relationships	⬭	⬭	⬭	⬭	⬭

Energy Efficiency of Office Buildings

Energy efficiency of a building is one of the most crucial concern that has to be concerned not only in relation to the environmental benefit attached to it, but also to the costs that is born by the building during it's life cycle. Energy is the highest consumer of operational cost of a building. Therefore, strategies shall be adapted to reduce the cost of energy in order to deduct the life cycle cost of a building.

8. Are there any energy efficient strategies adapted for your office building? *

Mark only one oval.

⬭ Yes

⬭ No

9. What are the adapted Energy efficient strategies to your building? *

Check all that apply.

- [ ] Natural ventilation
- [ ] Natural Lighting
- [ ] Energy saving lighting system
- [ ] Solar panel system
- [ ] Vertical greening systems ie. Green roofs/ walls
- [ ] Awareness programs on energy saving practices
- [ ] Building Management System (BMS)
- [ ] High Efficiency HVAC System
- [ ] Heat Recovery Ventilation (HRV) and Energy Recovery Ventilation (ERV)
- [ ] None of the above

10. Your view on "converting your office building into an energy efficient building" *

Mark only one oval.

- Highly Appreciate
- Appreciate
- Neutral
- Not appreciate
- Highly not appreciate
