Cooling Load Reduction strategies for Residential Buildings - A life cycle cost perspective

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has been accepted towards the partial fulfillment of the requirements for the degree of Master of Science in Construction Engineering and Management

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This thesis is dedicated to my mother, respected teachers, siblings and my friends.

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Abstract

Buildings consume tremendous amounts of energy for space cooling. Particularly, during the summer season, this consumption escalates, creating an overall sustainability concern. Several active and passive green building strategies have been proposed and successfully utilized, resulting in reduction in cooling load. However, the upfront cost associated with these strategies repels their adoption and decision makers often end up buying solutions which have huge operations and maintenance cost. This demands to have a life cyclic view of financial implications of green building strategies to manage cooling load. Therefore, the current study assimilates several green building active and passive strategies and simulates their thermal performance, obtaining the most optimum cooling load configuration. It is found that strategies grouped in Scenario 8 offer the minimum cooling load. Furthermore, life cycle cost analysis of each scenario is estimated and overall efficiency is evaluated to identify the most productive space cooling configuration. The results suggest that Scenario 13 has the minimum life cycle cost and presents the overall most optimum set of strategies. The findings will help the decision makers in selecting the most load-efficient and cost-effective green building strategies to help improve overall sustainability.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 General

Buildings consume approximately one third of the global energy (Kim, Kim, & Lee, 2019), which has grown by 60% during the period 2000-2010 and this demand is anticipated to be three times by the year 2050 (Chiesa, Grosso, Pearlmutter, & Ray, 2017). The two primary uses of this huge energy consumption in buildings include heating, ventilation and air-conditioning (HVAC) systems and functional appliances (Hughes, Chaudhry, & Ghani, 2011). Of this consumption, almost 85% is utilized in lighting, heating and maintaining thermal comfort. Ironically, this is under a severe energy crisis, especially in the developing countries particularly during the summer season which explains the high cooling load requirement of buildings (Kamal, 2012). Thus, the energy consumption for building space cooling is alarmingly high. However, increase in availability and use of insulating material, and efficient cooling and heating techniques could result in massive energy savings (Mihai, Tanasiev, Dinca, Badea, & Vidu, 2017). Considering this, many authors suggested utilizing passive and active cooling techniques to reduce cooling load consumption (Hughes et al., 2011; Kamal, 2012; Taleb, 2014) because of their several inherent gains (Zhang, Shen, & Wu, 2011).

There are various ways to incorporate the ideas of sustainable development in residential construction one of them is to reduce the cooling load of a building using various strategies which include active and passive strategies. Passive cooling emphasizes building envelope related features for cooling, whereas more energy efficient systems particularly lighting and HVAC are involved in active design (Chen, Yang, & Lu, 2015). Passive cooling reinforces the concept of green buildings. But despite their advantages, green buildings face a barrier of higher costs for energy-savings and green appliance design (Zhang et al., 2011). The cost factor complicates the selection and combination of various climate based strategies. It has been established that decision-making for such solutions cannot be solely based on upfront capital investment but the expenditure during the lifespan of a facility must also be considered. For this purpose, life cycle costing (LCC) which is an economic appraisal technique, considers building associated future running costs and is used to evaluate various investment alternatives. LCC merits considerable importance but its application in the construction sector is limited due to practical problems (Dwaikat & Ali, 2018). There is a constant scope of feasibility for reducing the cooling load consumption using several passive and active cooling techniques based on their LCC.

1.2 Problem Statement

The 50% energy consumption in buildings is used to maintain adequate indoor climate conditions by heating, cooling and ventilation for countries with warm climatic conditions (Chaudhry & Hughes, 2014). Considering the depletion of natural resources and current energy crisis, being faced in Pakistan it is need of the hour to reduce the energy consumption of buildings. One compatible solution is to opt green buildings. The design process that reduce cooling load leads to the reduced energy consumption, less harmful impact on natural resources, less emission of carbon dioxide and reduction of the life-cycle costs of the facility (Chau, Leung, & Ng, 2015).

Passive cooling reinforces the concept of green buildings. But despite their advantages, green buildings face a barrier of higher costs for energy-savings and green appliance design (Zhang et al., 2011). The cost factor complicates the selection and combination of various climate based strategies. It has been established that decision-making for such solutions cannot be solely based on upfront capital investment but the expenditure during the lifespan of a facility must also be considered. For this purpose, life cycle costing (LCC) which is an economic appraisal technique, considers building associated future running costs and is used to evaluate various investment alternatives. LCC merits considerable importance but its application in the construction sector is limited due to practical problems (Dwaikat & Ali, 2018). There is a constant scope of feasibility for reducing the cooling load consumption using several passive and active cooling techniques based on their LCC.

Despite its natural appeal to aid such decision-making, the literature is limited in investigation of cooling load utilization configurations as per their LCC. Chiesa, Grosso, Pearlmutter, and Ray (2017) worked on the development of innovative passive and hybrid cooling techniques for various climates. However, the economic evaluation of these techniques was not performed. Mihai et al. (2017) did an extensive research on the performance of a passive house located in Bucharest. While their work concluded that the passive house has reduced energy consumption with good thermal comfort, their study did not include LCC. Oliveira, Hagishima, and Tanimoto (2009) studied four envelope conditions in terms of their heat gains and losses for different climates in Brazil. However, their study underestimates the life cycle cost impact. Stephan and Stephan (2016) worked on the life cycle energy and cost requirements considering embodied, user-transport and operational energy reduction processes for residential buildings. While this study evaluated the life cycle energy and cost demand, it lacked in the analysis of prescribed measures. It was found in literature that various passive and active technologies have been used for significant reduction in operational energy of residential buildings but they lack in their cost analysis which complicates the selection process and leaves the user to work out if seemingly costly passive techniques will eventually be beneficial down the line.

So, based on this motivation, the current study provides decision makers and building planners with the most effective space cooling solution that has the most optimum economic performance. This study is expected to support decision makers in choosing the most optimum combination of passive and active strategies with lowest possible life cycle cost.

1.3 Research Objectives

i. To identify the active and passive strategies of cooling load reduction for residential buildings through literature review.
ii. To analyze and evaluate application of feasible and effective combination of strategies through simulation from the perspective of hot semi-arid climate of Pakistan.
iii. To perform LCC of all the attained combinations of strategies
iv. To suggest an optimized configuration for incorporating the proposed strategies in residential building construction projects

1.4 Research Significance

In the recent years Pakistan has been severely affected by electricity shortfall, environmental degradation, fuel shortage, rapid urbanization as well as poor industrial conditions. An introduction of sustainable building construction in industry can help fight this battle. The building with a reduced cooling load will result in the overall energy efficient building; it would not just be environment friendly, it will also have reduced energy consumption which will make it cost effective. If the same approach is applied to most of the residential buildings nationwide it will help to meet the energy crisis. Therefore, the introduction of optimized and cost efficient residential design in construction projects will help to resolve many problems being faced in construction industry of Pakistan.

1.5 Thesis structure

This thesis comprises five chapters. The order and brief description of these chapters is given below:

- Chapter 1. Introduction
- Chapter 2. Literature Review
- Chapter 3. Methodology
- Chapter 4. Results and discussions
- Chapter 5. Conclusions and Recommendations

Chapter 1. Introduction

This chapter includes general study background, problem statement, research objectives, research significance and thesis structure.

Chapter 2. Literature Review

This chapter covers requirement for cooling load reduction, sustainability in buildings, why residential buildings, passive and active cooling techniques, life cycle costing

Chapter 3. Methodology

This chapter covers initial study description, simulations and cost analysis.

Chapter 4. Results and discussions

This chapter covers the results in detail

Chapter 5. Conclusions and recommendations

Chapter 2

Literature Review

2.1 Requirement for Cooling Load Reduction

The rate at which sensible and latent heat must be removed from the space to maintain a constant space dry-bulb air temperature and humidity is referred to as cooling load. The cooling load accounts for the consumption of energy and resources. Buildings consume 40% of the global energy and are accountable for almost 40–50% of the world's greenhouse gas emissions (Hughes, Chaudhry, & Ghani, 2011). It is expected to escalate in the future due to the development, population growth and increasing demand for improved building's services (Nazi, Royapoor, Wang, & Roskilly, 2017). Almost 85% of building energy is utilized in lighting, heating and maintaining thermal comfort. Therefore the energy consumption for building space cooling is alarmingly high leading to a severe energy crisis, especially in the developing countries particularly during the summer season (Kamal, 2012).

2.2 Sustainability in Buildings

The application of sustainable construction approaches to create an energy efficient built environment is most commonly referred to as green buildings. In the literature, the terms green buildings, sustainable buildings, high-performance buildings, sustainable construction, green construction, and high-performance construction are interchangeably used. The approach of green building, unlike conventional buildings is to design, construct, and operate a building with minimal use of resources. The main factors driving their adoption are extended lifespan of green buildings, reduced operation and maintenance costs and energy-efficiency (Sharma, Saxena, Sethi, & Shree, 2011).

2.3 Why Residential Buildings

The residential buildings account for 75% of the building construction and 64% of the residential units are single-family houses. Energy efficiency improvements of the residential units is one of the most cost-effective ways to reduce energy use, achieve emission targets, resist climate change, fight fuel shortage as well as create employment (Psomas, Heiselberg, Duer, & Bjørn, 2016). Housing & Construction Sector is identified as the driver of economic growth by the Government of Pakistan. The annual shortfall of 270,000 housing units is observed at present while there is an accumulation of around 7.0 million units is in addition (Build Asia, 2018). Therefore, the reduction in the cooling load consumption of residential sector has a potential to meet the energy crisis and improve the life cycle cost.

2.4 Passive and Active cooling techniques

Passive cooling uses no or minimum power and has significantly reduced emissions and energy consumption (Lu, Xu, Wang, Yang, & Hou, 2016). Passive techniques can be categorized into two groups; the first one prevents or reduces heat gains by thermal control technologies and the second one dissipates heat gains by natural cooling strategies (Chiesa, Grosso, Pearlmutter, & Ray, 2017). Although passive techniques do not cater to all the space cooling loads, they reduce the dependence on conventional systems. On the other hand, active cooling techniques utilize mechanical means that require power input to cool a building. Literature reports that both passive and active techniques possess encouraging potential for reducing the building energy demand (Nazi, Royapoor, Wang, & Roskilly, 2017; Yang et al., 2017).

To extract the dominant passive and active strategies reported in the published literature, an extensive review has been performed. For this purpose, 37 research papers dealing with space cooling for residential buildings published between the period 2007-2019 have been thoroughly inspected. As a result, 23 passive and 5 active strategies have been identified. Further, content analysis on the selected papers was performed and average score of each strategy was calculated based on the reported percentage reduction in cooling load. These strategies were then ranked according to their average scores as mentioned in Table 1.

Table 1: Identified Passive Strategies

Rank	Passive Strategies	Average Score	Selected References
1	External wall insulation	5.94%	(Aktacir, Büyükalaca, & Yılmaz, 2010; Arababadi, Elzomor, & Parrish, 2017; Chen, Yang, & Lu, 2015; Chen, Yang, & Wang, 2017; Figueiredo, Figueira, Vicente, & Maio, 2016; Friess & Rakhshan, 2017; Ji, Lee, & Swan, 2019; Kamal, 2012; Oliveira, Hagishima, & Tanimoto, 2009; Taleb, 2014; Yang et al., 2017)
2	Shading	3.74%	(Chen et al., 2017; Chiesa et al., 2017; Friess & Rakhshan, 2017; Kamal, 2012; Kurian, Milhoutra, & George, 2016; Lavafpour & Sharples, 2015; McLeod, Hopfe, & Kwan, 2013; Samani, Leal, Mendes, & Correia, 2016; Taleb, 2014)
3	Glazing	2.04%	(Arababadi et al., 2017; Figueiredo et al., 2016; Friess & Rakhshan, 2017; Lavafpour & Sharples, 2015; McLeod et al., 2013; Nazi et al., 2017; Taleb, 2014)
4	Roof insulation	1.74%	(Aktacir et al., 2010; Arababadi et al., 2017; Chen et al., 2015; Chen et al., 2017; Figueiredo et al., 2016; Friess & Rakhshan, 2017; Kamal, 2012; Oliveira et al., 2009; Taleb, 2014; Yang et al., 2017)
5	Natural ventilation	1.64%	(Figueiredo et al., 2016; Friess & Rakhshan, 2017; Samani et al., 2016; Santamouris, Sfakianaki, & Pavlou, 2010; Taleb, 2014)
6	Floor insulation	1.51%	(Aktacir et al., 2010; Chen et al., 2015; Figueiredo et al., 2016; Kamal, 2012; Taleb, 2014)
7	Indirect radiative cooling (Nocturnal Cooling)	1.22%	(Bokor, Kajtár, & Eryener, 2017; Chiesa et al., 2017; Kamal, 2012; Lu, Xu, Wang, Yang, & Hou, 2016; Taleb, 2014)
8	Phase change materials (PCM)	1.20%	(Alam, Sanjayan, Zou, Ramakrishnan, & Wilson, 2017; Chiesa et al., 2017; Elnajjar, 2017; Sajjadian, Lewis, & Sharples, 2015)
9	White cool roof	1.15%	(Lu et al., 2016; Synnefa, Santamouris, & Akbari, 2007; Xu, Sathaye, Akbari, Garg, & Tetali, 2012;

			Zinzi & Agnoli, 2012)
10	Passive downdraught evaporative cooling	1.02%	(Chiesa et al., 2017; Kamal, 2012; Taleb, 2014)
11	Wind tower	1.01%	(Hughes et al., 2011)
12	Cool painting	0.76%	(Dabaieh, Wanas, Hegazy, & Johansson, 2015; Oliveira et al., 2009; Samani et al., 2016; Taleb, 2014)
13	Roof shape and form	0.64%	(Dabaieh et al., 2015)
14	Reduce infiltration rate	0.59%	(Chen et al., 2015; McLeod et al., 2013; Yang et al., 2017)
15	Increasing thermal mass in building walls	0.58%	(Friess & Rakhshan, 2017; McLeod et al., 2013)
16	Heat pipes operating under high-temperature natural ventilation airstreams	0.58%	(Chaudhry & Hughes, 2014)
17	Low-E metallic reflective coating	0.49%	(Zinzi & Agnoli, 2012)
18	Thermally activated building systems (TABS)-pipes embedded in the floor	0.32%	(Rijksen, Wisse, & Van Schijndel, 2010)
19	Air to air heat exchanger	0.29%	(Yang et al., 2017)
20	Green roof	0.26%	(Jiang & Tang, 2017; Taleb, 2014; Zinzi & Agnoli, 2012)
21	Solar control film	0.17%	(Yang et al., 2017)
22	Building layout and geometry	0.13%	(Chen et al., 2015; Chen et al., 2017)
23	Installation of solar panels	0.01%	(Mihai, Tanasiev, Dinca, Badea, & Vidu, 2017; Nazi et al., 2017)

As a result of the literature review 23 passive strategies were identified presented in Fig. 2-1

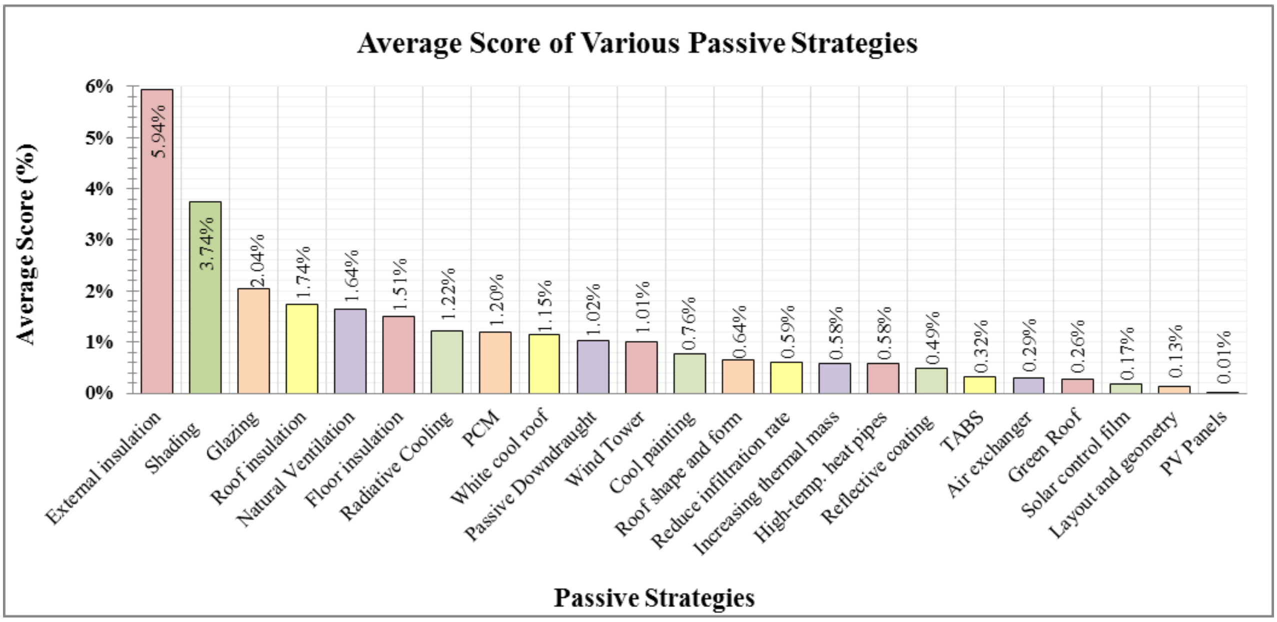

Figure 2-1: Identified passive strategies

Following the Pareto principle (80-20 Rule), 20% strategies were selected for further analysis and evaluation. Similar selection methods have been reported in previous studies (Ahmad, Thaheem, & Maqsoom, 2018). Because of this content analysis external wall insulation, shading, glazing, roof insulation and natural ventilation came out as 5 most effective passive strategies.

Insulation aids in reducing the space cooling load by limiting solar heat gain and is of great importance when a building requires mechanical cooling (Kamal, 2012). A great deal of attention has been paid to building insulation, highlighting rock wool, expanded polystyrene (EPS), extruded polystyrene (XEPS), cellular polyurethane as most prominent external wall insulation materials as well as Polystyrene (R5), Fiberglass (R10) as roof insulation materials for hot climates (Al-Homoud, 2005; Al-Sanea & Zedan, 2011; Kolaitis et al., 2013). Further, use of external shading devices is amongst the most effective strategies to decrease cooling load by limiting heat gains through fenestrations. Moreover, it also mitigates the future overheating risks (McLeod et al., 2013). External shading can take several forms including simple overhang, horizontal shading, vertical louvers and egg crate shading (Bellia, Marino, Minichiello, & Pedace, 2014; Shahdan, Ahmad, & Hussin, 2018).

The third most significant strategy is glazing. Thermal performance of the building envelope is improved by applying solar control measures to the glazing. It plays an important role in lowering cooling demand (Friess & Rakhshan, 2017). The most efficient glazing units for hot humid climates are low-e glass (soft coated), smart glass (absorptive + reflective + low-e-green), 6mm low-e (soft coated)+12mm air space+6mm clear (LECLR2) and 6mm blue HRG (low-e soft coated)+12mm air space+6mm clear (HRBLULE2) (Rashid, Ahmad, Malik, & Ashraf, 2016; Yaşar & Kalfa, 2012). The next strategy is natural ventilation which is an effective way to dissipate excessive heat gain from the building. A growing interest has been observed in the use of natural ventilation to reduce cooling load as well as to improve indoor air quality (Samani et al., 2016; Taleb, 2014). Cross ventilation through windows and night ventilation are influential strategies (Aflaki, Mahyuddin, Mahmoud, & Baharum, 2015).

Similarly, 5 active strategies were identified and ranked according to their respective average scores, as given in Table 2. The most significant of them as per Pareto selection came out to be lighting system (Arababadi et al., 2017; Chen et al., 2015; Kurian, Milhoutra, & George, 2016b; Nazi et al., 2017). Artificial lighting is responsible for increasing the heat gain within spaces by creating internal loads. Decreasing the power density results in reduced cooling load (Arababadi et al., 2017). Light Emitting Diode (LED) and Compact Fluorescent Light (CFL) in lighting technology is recommended replacement of incandescent lamps (Kurian et al., 2016b; Nazi et al., 2017). A residential building's overall cooling load is reduced by using CFL as they emit 75% less waste heat as compared to similar incandescent bulbs (Sadineni, France, & Boehm, 2011). LED lighting has controlled thermal effect because the LED chip has heat sink divided across it which is used to reduce the cooling load of buildings (Ahn, Jang, Leigh, Yoo, & Jeong, 2014).

Table 2: Identified Active Strategies

Rank	Active Strategies	Average Score	Selected References
1	Lighting System	19.08%	(Arababadi et al., 2017; Chen et al., 2015; Kurian et al., 2016; Nazi et al., 2017)
2	Equipment	8.70%	(Arababadi et al., 2017; Nazi et al., 2017)
3	occupant-based measures	5.36%	(Friess & Rakhshan, 2017)
4	Desiccant cooling	2.80%	(Hughes et al., 2011; Kamal, 2012)
5	Operation settings	2.50%	(Nazi et al., 2017)

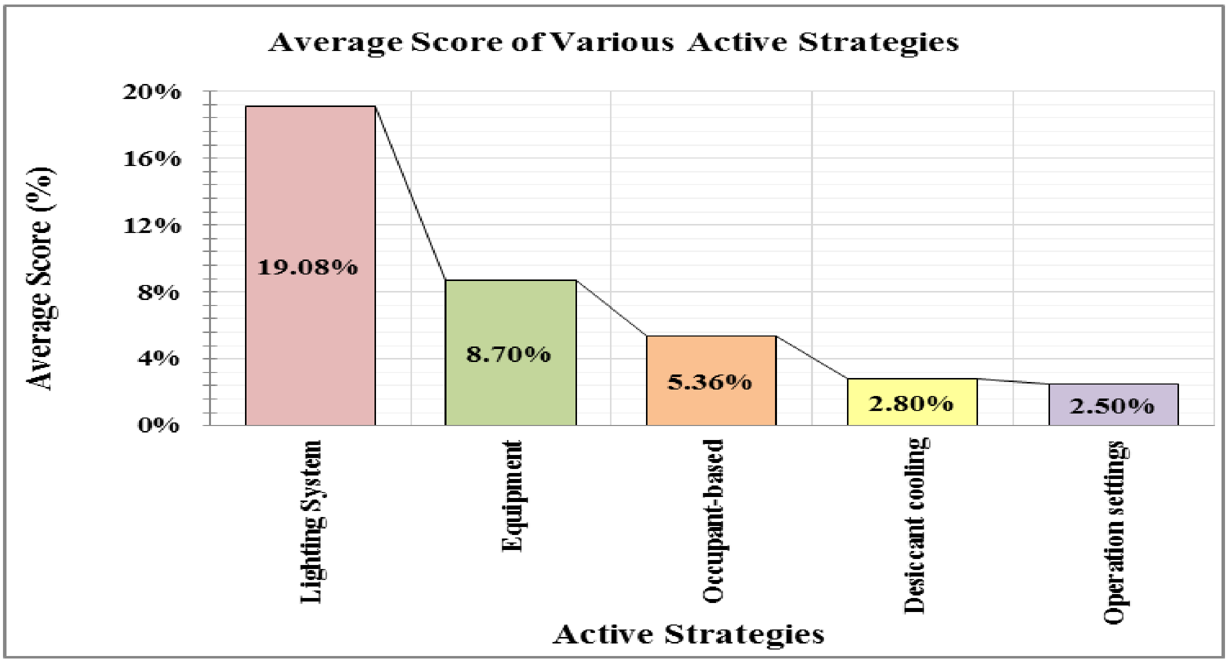

Figure 2-2: identified active strategies

It is observed that the building cooling demand is expected to increase 72% by the year 2100. Therefore, it is significant to optimize the envelope and improve the active cooling systems (Friess & Rakhshan, 2017). A number of studies have been conducted in this regard. Yang et al. (2017) established a generalization method for the reduction of anthropogenic heat by application of efficient building systems and retrofitting strategies. Nazi et al. (2017)

demonstrated a strategy for cooling load reduction based on building's thermal analysis. Lu et al. (2016) reviewed the trends as well as advancements of passive radiative cooling technique. Hughes et al. (2011) assessed the implementation of active and passive cooling solutions in buildings. Importance of passive house and building envelope related measures has also been highlighted by performing analysis considering various climates (Dabaieh et al., 2015; Figueiredo et al., 2016; Friess & Rakhshan, 2017; Mihai et al., 2017; Oliveira et al., 2009; Taleb, 2014). These experimental and modeling studies made significant contribution to the body of knowledge. However, these studies substantially lack in the economic performance of incorporated strategies. For such an assessment, life cycle based cost and expenditure related information can help the decision makers.

2.5 Life Cycle Costing

Life cycle costing (LCC) evaluates the expected economic performance of a building throughout its life cycle which includes the building design and construction, operation, maintenance and building disposal costs at the end of its serviceable life (Dwaikat & Ali, 2018). Different design alternatives are compared using LCC of a building, considering the savings and life cycle cost accompanying each design option. The ISO standard 15686–5:2017 provides four main categories including design and construction cost, operation cost, maintenance cost and the end of life cost in a well-defined cost breakdown structure for building LCC. More cost components in detailed are listed under each category to cover all the appropriate costs related to a building throughout its life cycle (ISO, 2017).

There are few studies addressing quantification of building life cycle assessment. Sharma et al. (2011) have worked on life cycle assessment (LCA) to see which phase and type of building consumes more energy. However, their study is limited in terms of evaluation of energy reduction measures. A recent study has quantified life cycle energy and cost requirements considering embodied, user-transport and operational energy reduction processes for residential buildings (Stephan & Stephan, 2016). While this study evaluated the life cycle energy and cost demand, there is a limitation regarding modeling and analysis of the prescribed measures.

Based on these gaps in the literature, the current study sets out to perform a detailed LCC of passive-active strategies combinations to identify the optimum sequence and help the decision maker in reaching to a practical decision.

Chapter 3

Methodology

3.1 Introduction

In order to achieve the desired research objectives, research methodology provides guidance in conducting the research. It helps researcher to highlight the relevant tools and techniques to carry out the process with the limitation of time and resources. Therefore, this chapter discusses the tools and techniques utilized in the study. Multiple techniques were used during the research process i.e. literature review, cooling load simulations and lifecycle costing.

A four-stage research methodology as shown in Fig.3-1, has been developed. The details are explained in subsequent sections.

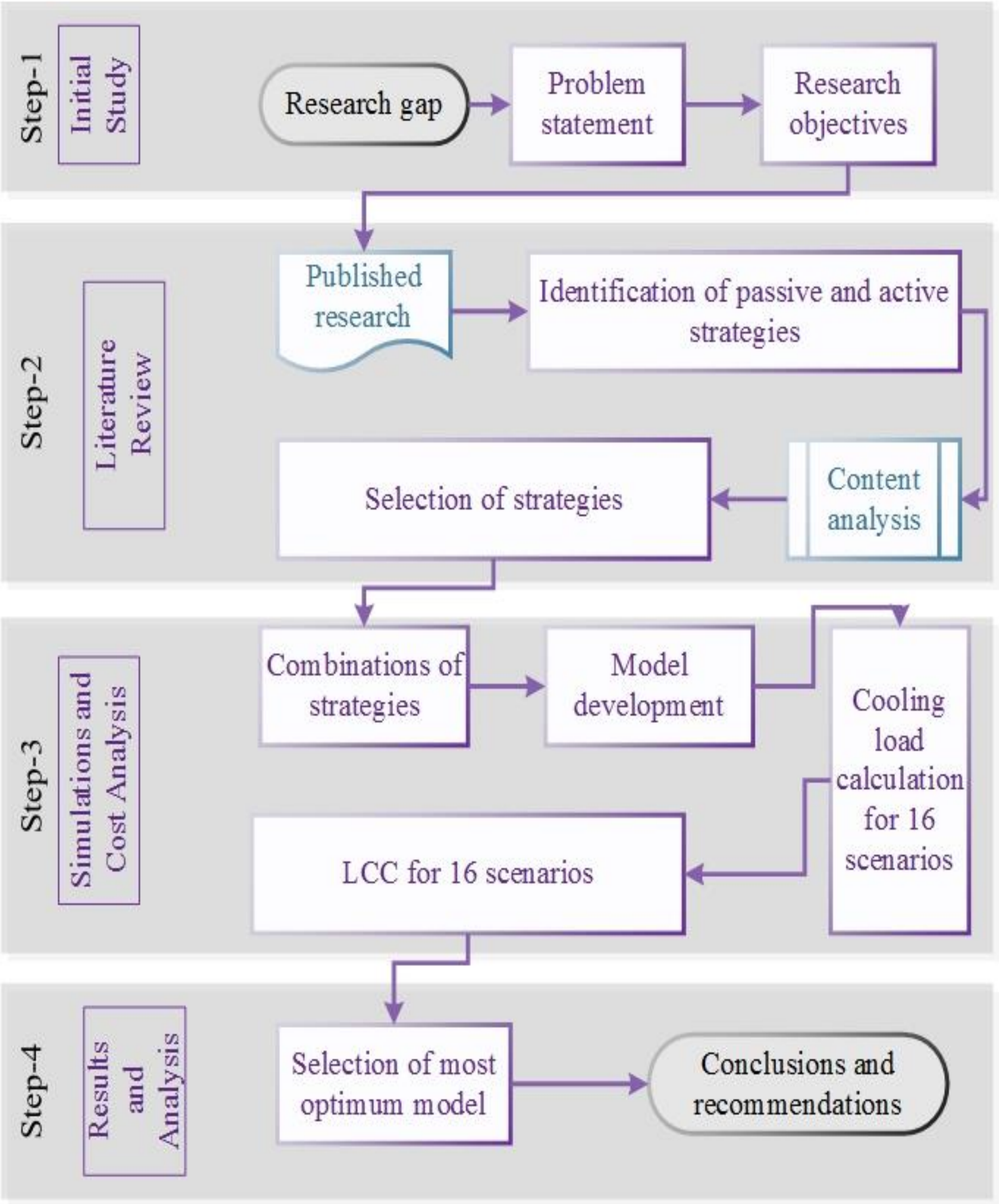

Figure 3-1: Research Methodology Flowchart

3.2 Step-1

In the first stage, critical review of recent studies was carried out to find the research gap. Research articles published in well reputed journals on passive strategies, cooling load reduction measures, active strategies and life cycle costing (LCC) were analyzed. This helped in identifying a research gap as limitation of cooling load utilization configurations according to their LCC. Although various passive and active strategies have been used for significant load reduction of residential buildings, they lack in a proper cost analysis required for decision-making. Considering this limitation, the objectives of current study were devised to fill the identified gap. This study proposes an optimized model option to reduce cooling loads and has the lowest life cycle cost over its design period.

3.3 Step-2

Based on the objectives, an extensive literature review was carried out to identify passive and active strategies for cooling load reduction. While searching the related literature, ScienceDirect, Google Scholar, Scopus, Taylor and Francis, and Emerald libraries were used. To cover most of the available literature, a total of 62 research papers were retrieved initially and screening was performed to select the most relevant papers, resulting in 37 papers.

These papers were then analyzed in detail to identify the passive and active strategies and their reported percentage contribution in cooling load reduction. A total of 23 passive and 5 active strategies were identified and ranked according to their average scores calculated using the percentage reduction as previously mentioned and presented in Table 1. In total, 20% identified strategies from each category comprising of external wall insulation, shading, glazing, roof insulation and natural ventilation as passive and lighting system as active strategies were selected for further analysis and evaluation.

3.4 Step-3

After the content analysis and selection of strategies, there was a need to identify the applicable combinations of selected strategies which could lead to the reduced cooling load consumption. This was an iterative process, possibly leading to 12,480 simulations. For this purpose, Taguchi based Design of Experiment (DoE) is used which allows for an effectively reduced number of repetitions using orthogonal arrays that contains a finite set of variable combinations (Davis & John, 2018; Yi, Srinivasan, & Braham, 2015). The number of simulations was then reduced to 16. DesignBuilder V6.1 is used for carrying out simulations since it is integrated with EnergyPlus™ that allows simulating through EnergyPlus™ graphical interface.

3.4.1 Base case building

A residential building having plot area of 2250 ft^2 and total covered area of 3200 ft^2 located in Lahore, Pakistan was selected as a base case. According to Köppen and Geiger climate classification Lahore is classified as BSh (hot semi-arid climate) with average annual rainfall of 607 mm. June is the hottest month of the year with an average temperature of 33.9 °C (Data.org, 2019). Some general information regarding the residential unit is shown in Table 3.

Table 3: Base Case Information

Location	Paragon City, Lahore
Total plot area	2250 ft^2
Number of Storeys	2
Total covered area	1693+1507=3200 ft^2
Orientation	South Facing
Ceiling height	11 ft

The layout of the building has been shown in Fig. 3-2

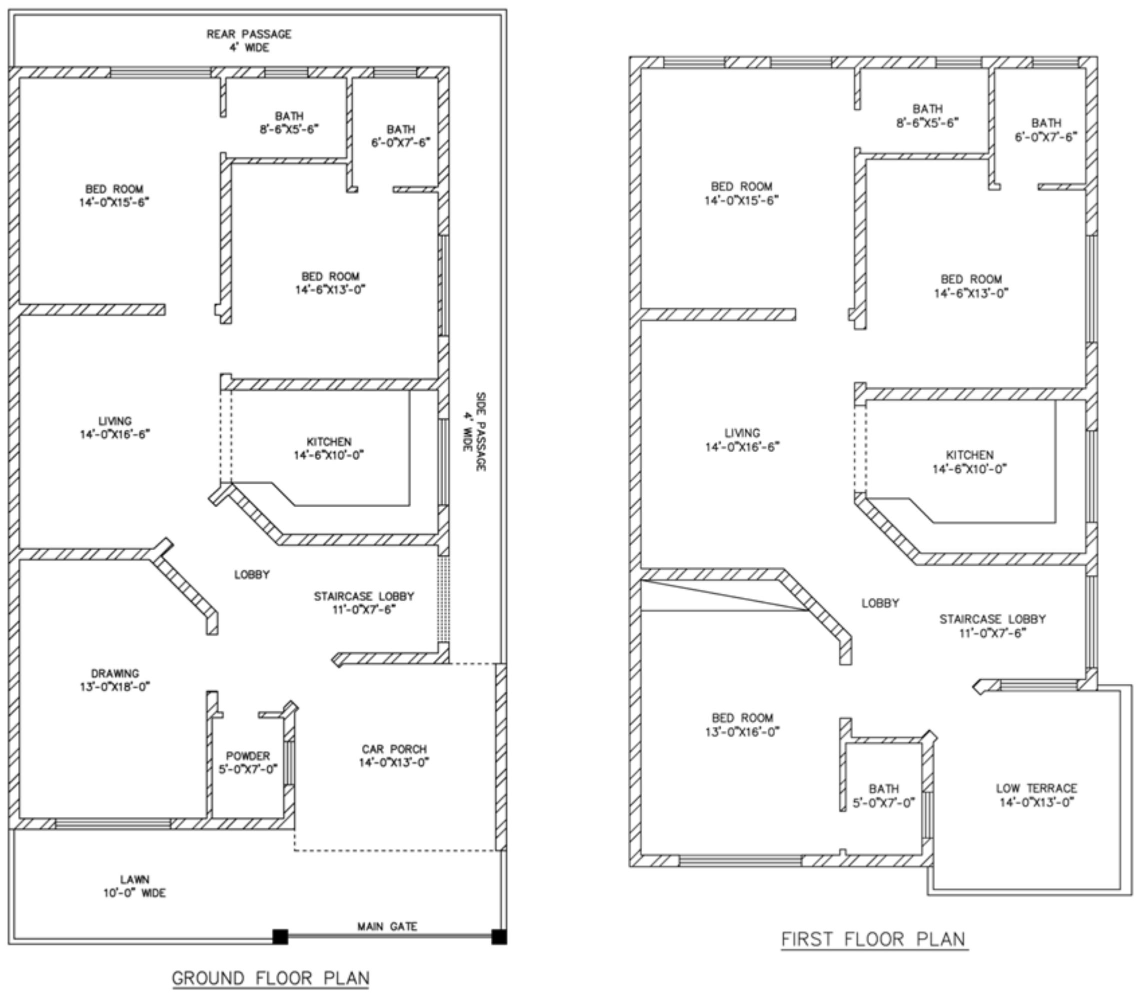

Figure 3-2 Layout of Building

The model of a base case was developed in DesignBuilder V6.1 as shown in Fig. 3-3. It was divided into different zones depending upon the usage of each zone. Location, site details and weather input data were assigned accordingly mentioned in Fig. 3-4.

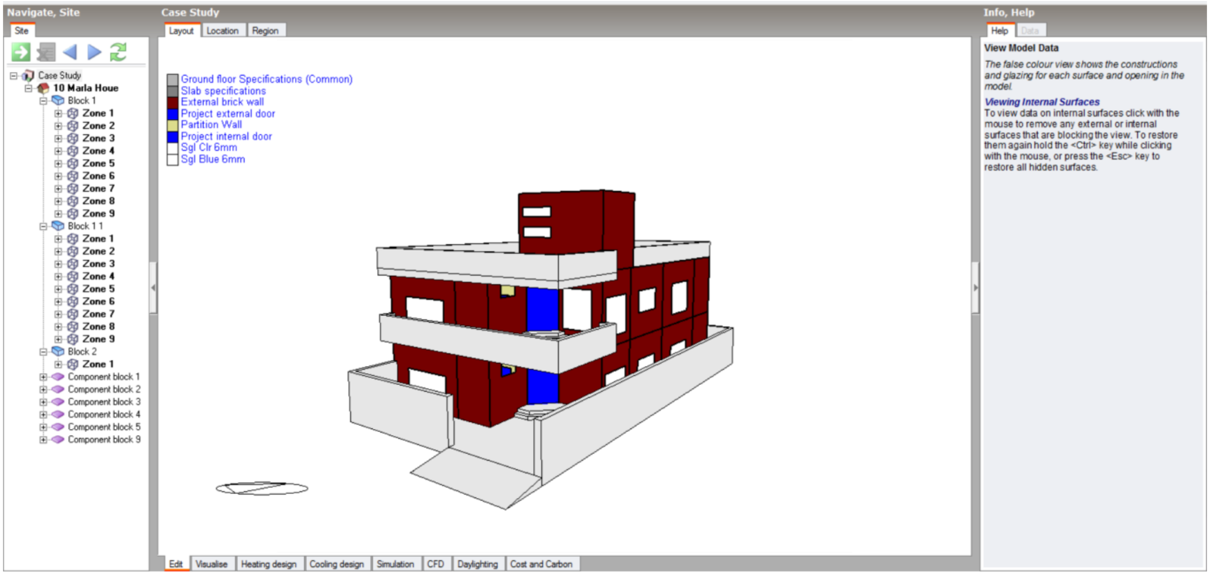

Figure 3-3: Base case model

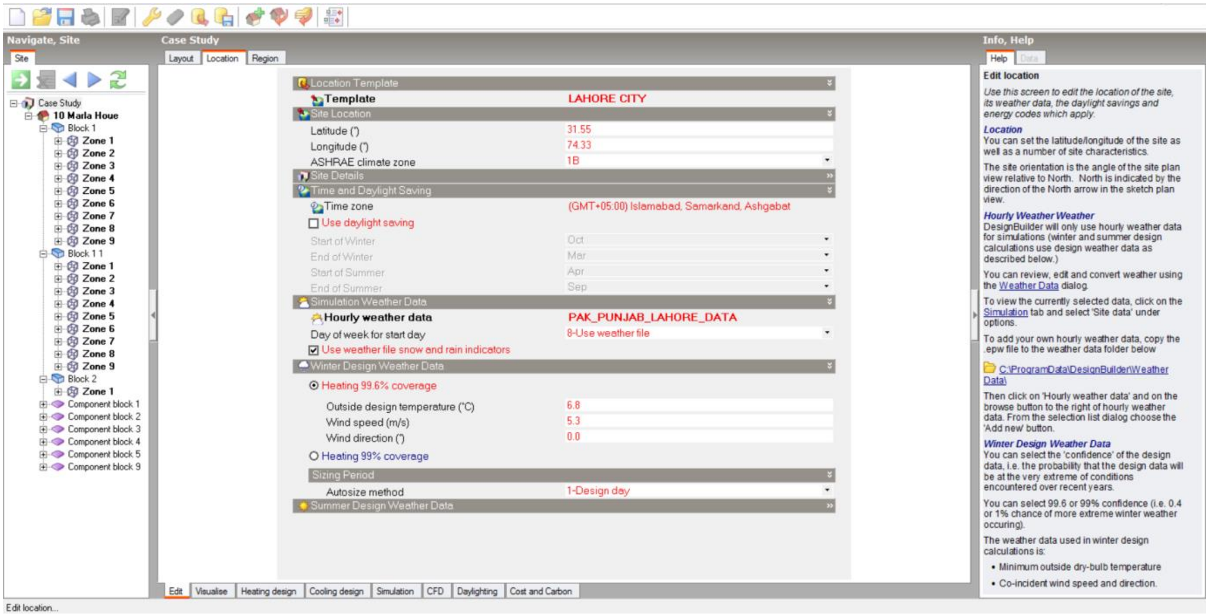

Figure 3-4: Model data input

Further construction details including wall specifications, slab details, shading, windows and lighting were entered according to the as built design as shown in Fig. 3-5 and Fig. 3-6.

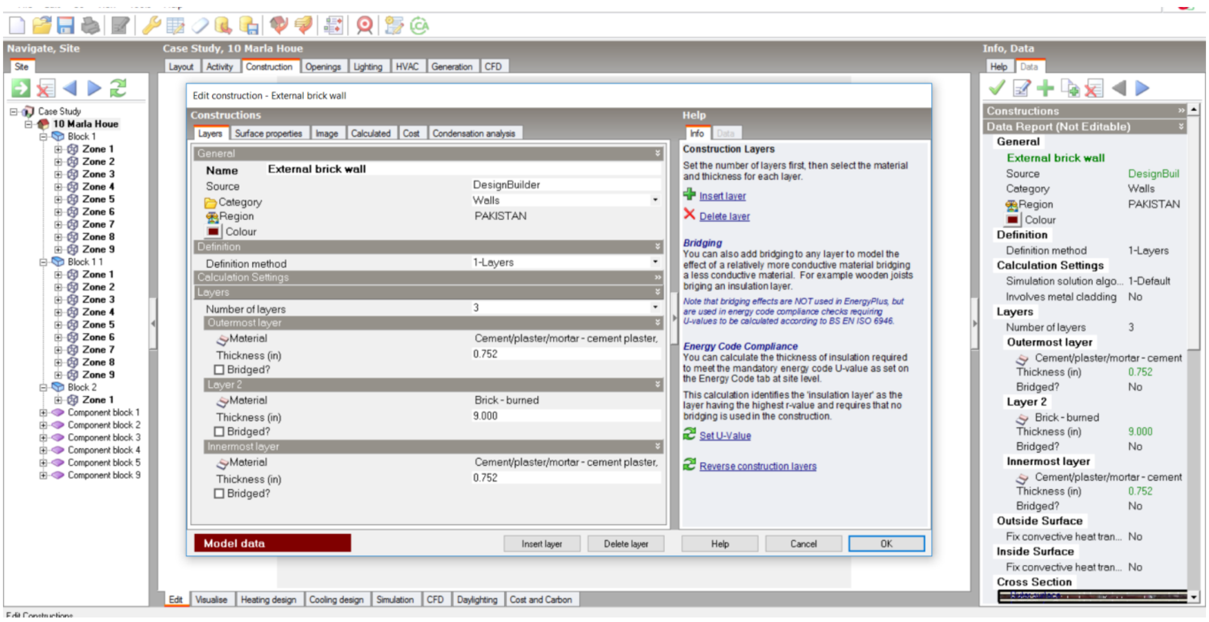

Figure 3-5: External wall specifications

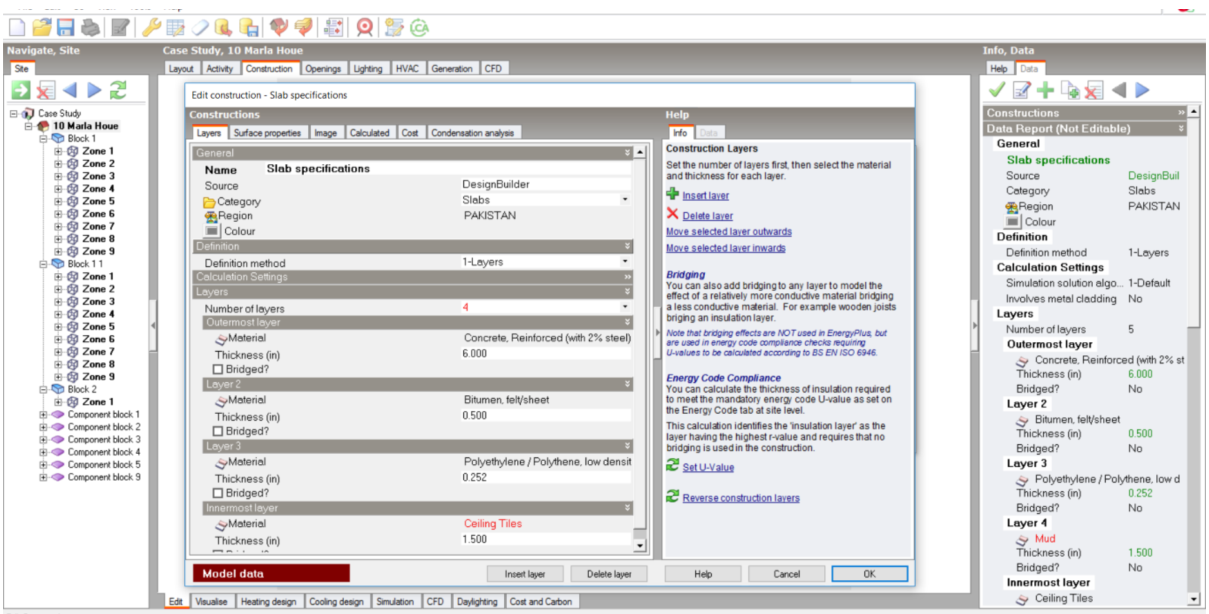

Figure 3-6: Slab specifications

The cooling load consumption for base case (without applying any strategy) was calculated.

3.4.2 Cooling load calculation for 16 scenarios

The same procedure as mentioned earlier was followed and 16 identified scenarios were modeled for the calculation of cooling load with varying inputs of external wall insulation, shading, glazing, roof insulation, natural ventilation and lighting system.

3.4.3 LCC for 16 scenarios

Afterward, LCC of the case building was calculated using cradle to grave method including all the phases of a building (design and construction, operation, maintenance, and end of life). The period of analysis was kept 60 years, starting from 2018 (construction start date) to 2077 (expected end of life). The official currency of Pakistan i.e. Pakistani rupees (PKR) was used for calculation. According to the current statistics 1US$ = PKR 145.88. The inflation rate was taken as 7.75% based on the historical trend of inflation rate for the past 60 years in Pakistan (statistics, 2019). Design and construction cost for base case was provided by the contractor, and operation and maintenance costs were calculated based on energy, water, natural gas consumption and replacement costs of respective items. End of life cost was calculated for the current year and its future value was determined using Eq. (1), where ***F*** is the future value, ***P*** is the cost of base year, ***e*** is the expected percentage of inflation and ***n*** is the number of years under consideration.

$$F = P(1+e)^{n} \qquad (1)$$

The LCC of the base case is explained in this section. Capital cost of base case provided by contractor is shown in Table 4

Table 4: Capital cost of base case

Capital Cost				
Activity	***Description***	***Unit Price***	***Quantity***	***Cost in PKR***
Backfilling in Footings	Earthfill	25 Rs/cft	3536cft	88400
	Brick Ballast	-	-	44200
	Brick Tiles	14	2428	34000
	A.C Pipes	-	-	30600
	Bitumen	-	-	13600
	Polythene sheet	-	-	10200
	Mud	-	-	10200
	Labor Cost for boring upto 120 ft	-	-	14000
	Anti-Termiting	-	-	13800

	Miscellaneous	-	-	34000
	Chips in carporch	-	-	13600
	Bills	-	-	17000
	Taxes	-	-	17000
Total				**340600**
Grey Structure	Premium Class Bricks	9.5/Brick	88000	836000
	Aggregate	78 Rs/cft	2920 cft	227760
	Cement	600/Bag	1105 Bag	663000
	Steel	102000 Rs/Ton	6.73 Ton	686800
	Sand	30 Rs/cft	4760 cft	142800
	Labor rate	325 Rs/ft2	3400ft2	1105000
	Other Cost	-	-	200000
	Electrical items in grey structure	-	-	85000
	Plumbing items in grey structure	-	-	170000
Total				**4116360**
Finishing Material	Electrical Items	-	-	425000
	Paints	-	-	374000
	Polish Works	-	-	85000
	Sanitary Items	-	-	465000
	Granites	-	-	136000
	False Ceilings	-	-	142800
	Aluminium Windows	-	-	187000
	S.S Railings	-	-	37400
	Safety Grills	-	-	74800
	Steel Gate	-	-	68000
	Wallpapers	-	-	72000
	Wood Works	-	-	714000
	Tiles	-	-	697000
Total				**3478000**
Labor Costs (Finishing Material)	Electrician			51000
	Plumber			40800
	Tile Mason			210800
	Carpenter			251600
	Painter			221000
	Polish(Painter)			68000
	Other Materials			187000
Total				**1030200**
NET TOTAL				**8,965,160.00**

The operating costs of base case are shown in Table 5. Energy consumption was calculated using DesignBuilder software which came out to be 10864.05kWh/Yr for the base case then energy cost was calculated using schedule of electricity tariff provided by Lahore Electric Supply Company (LESCO) i.e.

- For first 100 Units - 13.85 Rs/KWh
- 101-200 Units - 15.86 Rs/KWh
- 201-300 Units - 16.83 Rs/KWh
- 301-700 Units - 18.54 Rs/KWh
- Above 700 Units- 20.94 Rs/KWh

The energy cost for the base case is calculated as follows

Energy cost = (100kWh/month * 12months * 13.85 Rs/kWh) + (99kWh/month * 12months * 15.86 Rs/kWh) + (99kWh/month * 12months * 16.83 Rs/kWh) + (399kWh/month * 12months * 18.54 Rs/kWh)+ (208.34Wh/month * 12months * 20.94 Rs/kWh)

Energy cost = 196576 Rs per year.

This cost is projected for next 60 years using the inflation rate of 7.75% provided by Pakistan Bureau of Statistics. Water and natural gas consumption was determined using utility bills of the facility and their cost was determined based on the consumption pattern and tariffs provided by authority. A total of operating cost was then determined.

Table 5: Operating cost of the base case

Operating Cost				
Sr No.	***Year***	***Energy Cost***	***Water Cost***	***N.Gas Cost***
1	2018	196576	20197	6498
2	2019	211811	21762	7002
3	2020	228226	23449	7544
4	2021	245914	25266	8129
5	2022	264972	27224	8759

6	2023	285508	29334	9438
7	2024	307634	31608	10169
8	2025	331476	34057	10957
9	2026	357165	36697	11806
10	2027	384846	39541	12721
11	2028	414671	42605	13707
12	2029	446808	45907	14770
13	2030	481436	49465	15914
14	2031	518747	53298	17148
15	2032	558950	57429	18477
16	2033	602269	61879	19909
17	2034	648945	66675	21451
18	2035	699238	71842	23114
19	2036	753429	77410	24905
20	2037	811819	83409	26835
21	2038	874735	89874	28915
22	2039	942527	96839	31156
23	2040	1015573	104344	33571
24	2041	1094280	112431	36172
25	2042	1179087	121144	38976
26	2043	1270466	130533	41996
27	2044	1368927	140649	45251
28	2045	1475019	151549	48758
29	2046	1589333	163294	52537
30	2047	1712506	175949	56608
31	2048	1845226	189586	60996
32	2049	1988231	204278	65723
33	2050	2142319	220110	70816
34	2051	2308348	237169	76304
35	2052	2487245	255549	82218
36	2053	2680007	275354	88590
37	2054	2887707	296694	95456
38	2055	3111505	319688	102853
39	2056	3352646	344464	110825
40	2057	3612476	371160	119414
41	2058	3892443	399925	128668
42	2059	4194108	430919	138640
43	2060	4519151	464315	149384
44	2061	4869385	500299	160962
45	2062	5246762	539072	173436
46	2063	5653386	580851	186878
47	2064	6091524	625866	201361
48	2065	6563617	674371	216966

49	2066	7072297	726635	233781
50	2067	7620400	782949	251899
51	2068	8210981	843628	271421
52	2069	8847332	909009	292456
53	2070	9533001	979457	315122
54	2071	10271808	1055365	339544
55	2072	11067873	1137156	365858
56	2073	11925634	1225285	394212
57	2074	12849870	1320245	424764
58	2075	13845735	1422564	457683
59	2076	14918780	1532813	493153
60	2077	16074985	1651605	531373
Total		**220957679**	**22702038**	**7303948**
TOTAL Operational Costs				**250,963,665**

The maintenance costs of base case are shown in Table 6. Maintenance of air conditioning, plumbing and lighting fixtures were used according to the company rates, whereas general cleaning and landscaping were determined using local area rates.

Table 6: Maintenance costs of base case

Building Maintenance Cost						
Year	***Maintenance of air conditioning***	***Maintenance of Plumbing (every 10yrs)***	***Maintenance of lighting***	***Security services***	***General cleaning***	***Landscaping***
2018	24000		48000	Nil	72000	24000
2019	25860		51720	Nil	77580	25860
2020	27864		55728	Nil	83592	27864
2021	30024		60047	Nil	90071	30024
2022	32350		64701	Nil	97051	32350
2023	34858		69715	Nil	104573	34858
2024	37559		75118	Nil	112677	37559
2025	40470		80940	Nil	121410	40470
2026	43606		87213	Nil	130819	43606
2027	46986	501038	93972	Nil	140957	46986
2028	50627		101254	Nil	151882	50627
2029	54551		109102	Nil	163652	54551
2030	58779		117557	Nil	176336	58779
2031	63334		126668	Nil	190002	63334
2032	68242		136484	Nil	204727	68242

2033	73531		147062	Nil	220593	73531
2034	79230		158459	Nil	237689	79230
2035	85370		170740	Nil	256110	85370
2036	91986		183972	Nil	275958	91986
2037	99115	539868	198230	Nil	297345	99115
2038	106796		213593	Nil	320389	106796
2039	115073		230146	Nil	345220	115073
2040	123991		247983	Nil	371974	123991
2041	133601		267201	Nil	400802	133601
2042	143955		287909	Nil	431864	143955
2043	155111		310222	Nil	465334	155111
2044	167132		334265	Nil	501397	167132
2045	180085		360170	Nil	540255	180085
2046	194042		388083	Nil	582125	194042
2047	209080	581708	418160	Nil	627240	209080
2048	225284		450567	Nil	675851	225284
2049	242743		485486	Nil	728229	242743
2050	261556		523111	Nil	784667	261556
2051	281826		563653	Nil	845479	281826
2052	303668		607336	Nil	911003	303668
2053	327202		654404	Nil	981606	327202
2054	352560		705120	Nil	1057681	352560
2055	379884		759767	Nil	1139651	379884
2056	409325		818649	Nil	1227974	409325
2057	441047	626790	882094	Nil	1323142	441047
2058	475228		950457	Nil	1425685	475228
2059	512059		1024117	Nil	1536176	512059
2060	551743		1103486	Nil	1655229	551743
2061	594503		1189006	Nil	1783510	594503
2062	640577		1281154	Nil	1921732	640577
2063	690222		1380444	Nil	2070666	690222
2064	743714		1487428	Nil	2231143	743714
2065	801352		1602704	Nil	2404056	801352
2066	863457		1726914	Nil	2590370	863457
2067	930375	675366	1860749	Nil	2791124	930375
2068	1002479		2004958	Nil	3007436	1002479
2069	1080171		2160342	Nil	3240513	1080171
2070	1163884		2327768	Nil	3491652	1163884
2071	1254085		2508170	Nil	3762255	1254085
2072	1351277		2702553	Nil	4053830	1351277
2073	1456001		2912001	Nil	4368002	1456001
2074	1568841		3137681	Nil	4706522	1568841
2075	1690426		3380852	Nil	5071278	1690426
2076	1821434		3642868	Nil	5464302	1821434

2077	1962595		3925190	Nil	5887785	1962595
Total	**26,976,724**	**2,924,769**	**53,953,449**		**80,930,173**	**26,976,724**
TOTAL Maintenance Costs						**191,761,840**

End of life cost was calculates using the rates provided by Pakistan Works Department and calculation of salvage value of the recycled materials that included 60% steel and bricks. The end of life cost is presented in Table 7.

Building End of Life Cost Estimate.					
Description	***Area***	***Unit Waste***	***Waste Quantity***	***Unit cost***	***Total cost***
Site clearing, waste transport & labor cost	$251m^2$	1.2676 m3/m2	318.17m3	800 Rs/m3	254,536
Indirect cost 10%					25,454
Resale Value of recycled materials					702,000
Total cost based on 2019 prices					422,010
Total cost in 2077					**32,027,638**

The overall summary of LCC breakdown for the base case is presented in Table 7.

Table 7: LCC breakdown for base case

Building Total Life Cycle Cost-Base Case		
Capital Cost	8,965,160.00	2%
Operating Cost	250,963,665.02	60%
Maintenance Cost	191,761,839.65	46%
End of life Cost	32,027,638.25	8%
TOTAL	**419,663,026**	100%

Market rates for materials such as wall insulation, roof insulation, low e glass, double glazed windows and labor were obtained for the introduced strategies and LCC for 16 identified cases was calculated based on the same procedure.

3.5 Step-4

After the calculation of cooling load and LCC for each scenario, the combined score for each option is calculated giving 50% weightage to both cooling load and LCC. This score yields the best optimum combination of strategies with minimum value of life cycle cost and cooling load. The introduction of passive and active strategies in residential buildings not only reduces the cooling load thus decreasing the dependency on cooling systems but it also significantly reduces its life cycle cost.

Results and discussions

4.1 Impact of strategies on cooling load

The cooling load of a building depends on many factors such as climatic conditions, insulation materials, shading techniques, glazing, lighting system, equipment used, etc. This study presents the optimum design of a building depending upon the cooling load consumption during summer. The analysis of base case cooling load obtained from simulations is presented in Fig. 4-1.

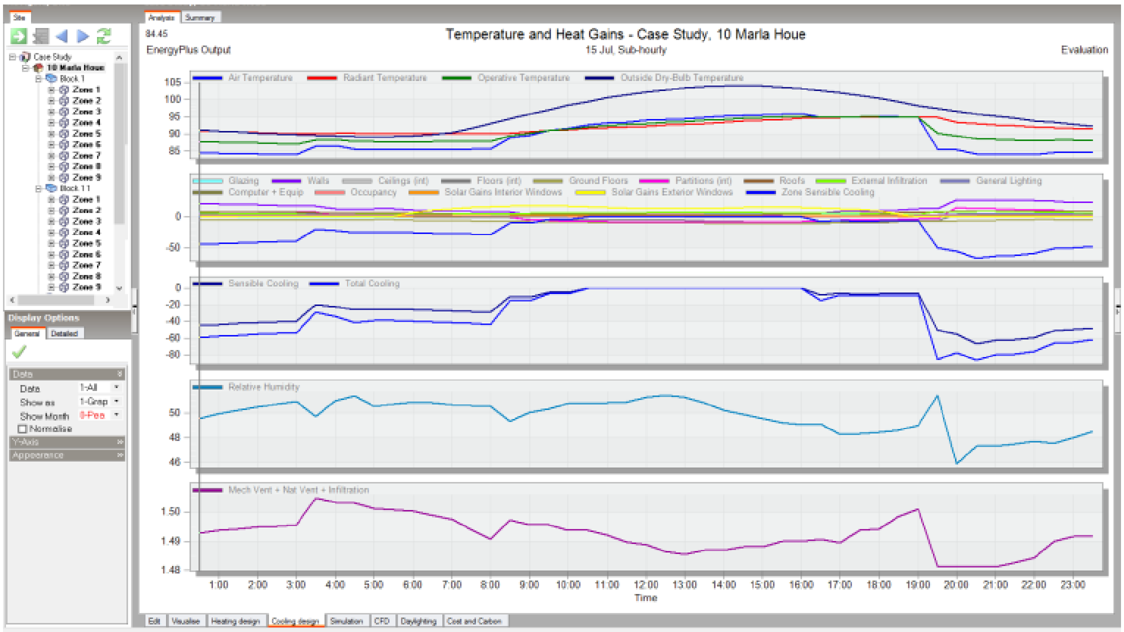

Figure 4-1: Analysis result of base case cooling loads

Similarly, cooling loads for other 16 scenarios with different design combinations of wall insulation, shading devices, glazing, natural ventilation and lighting system were simulated in DesignBuilder V6.1. The resulting cooling load from each combination is presented in Fig. 4-2.

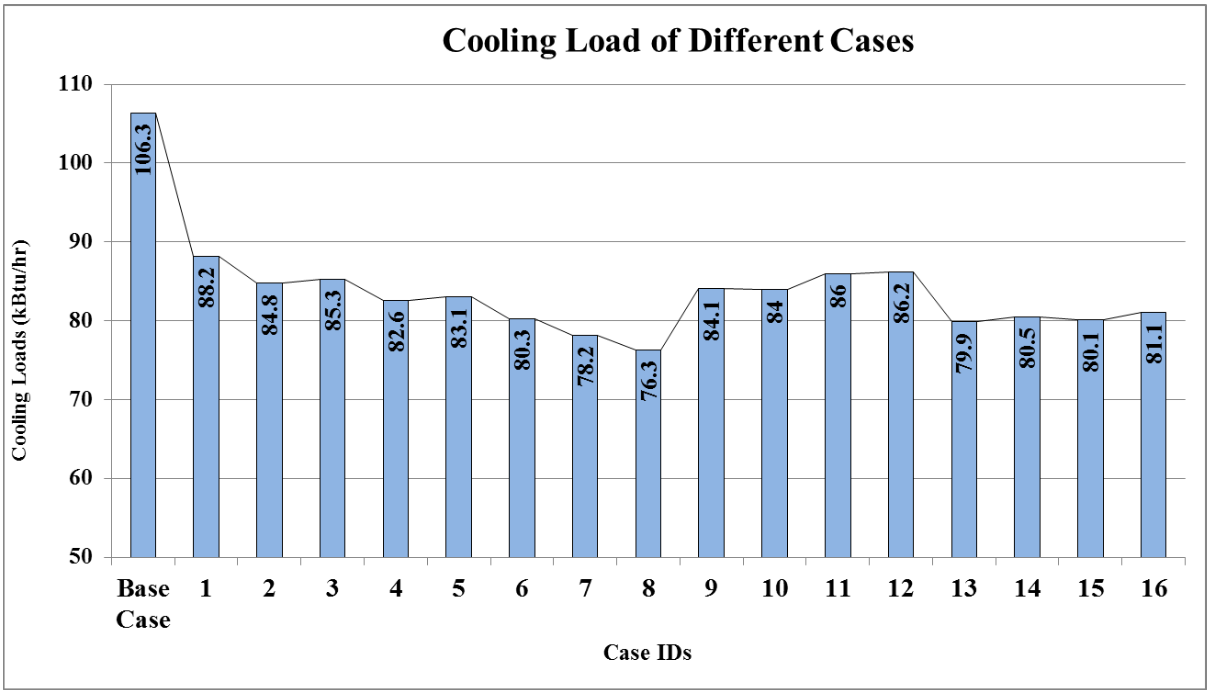

Figure 4-2: Comparison of cooling loads for all scenarios

The graph clearly shows that the base case has the highest cooling load outcome of 106.3 kBtu/hr, whereas Scenario 8 comprising of expanded polystyrene (EPS) wall insulation, vertical louvers as an external shading device, double glazed windows having a combination of 6mm blue HRG (low-e soft coated)+12mm air space+6mm clear (HRBLULE2), polystyrene (R5) as a roof insulation, natural ventilation through windows and LED lighting system result in a minimum consumption of cooling load (76.3 kBtu/hr). This scenario shows a 28.2% reduction in overall building cooling load due to the limited heat gains from building envelope and lighting. Although the lowest cooling load among all the presented options for the case building has been obtained, the result cannot be solely based on the outcome of cooling load and life cycle costing must be considered for sustainable decision-making. Some previous studies have reported similar trend of cooling load reduction in the context of residential buildings ranging from 26.8% to 33.6% (Friess & Rakhshan, 2017).

4.2 Impact of strategies on LCC

LCC of a building is another critical parameter for the selection of the most optimum option out of the presented scenarios. After the simulation of cooling loads, the LCC of each case was evaluated and compared as shown in Fig. 4-3.

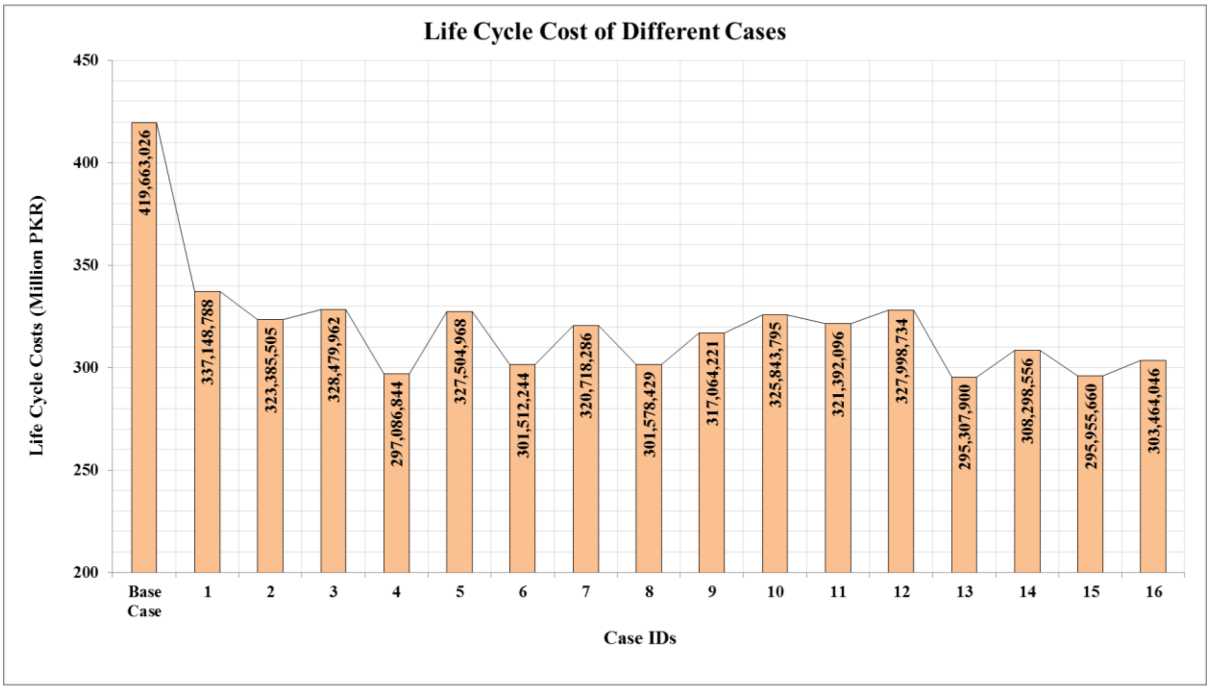

Figure 4-3: Compilation of LCC for all scenarios

It is evident that Scenario 13 comprising of cellular polyurethane for external wall insulation, egg crate shading as an external shading device, soft coated low-e glass for windows, fiberglass (R-10) as roof insulation, cross ventilation through windows and LED lighting system has the minimum LCC value of PKR 295,307,900 (US$ 2,024,390) amongst all other cases, whereas the base case has the highest value of PKR 419,663,026 (US$ 2,876,867) This combination resulted in 29.6% reduction in LCC as compared to the base case. The previously highlighted minimum cooling load consumption case (Scenario 8) is different because it has a higher value of LCC due to higher operational cost.

4.3 Combined effect of cooling load and LCC

Table 9 represents the 16 identified combinations of passive and active strategies along with their cooling loads, obtained by applying strategies of each scenario to the building model and simulating in DesignBuilder V6.1, and the LCC values of respective scenarios. The cooling loads of all the varying inputs has been arranged in ascending order and plotted in a graph against LCC of the respective scenarios, as presented in Fig. 4-4.

Table 8: Cooling load and LCC output

Scenario	External wall insulation	Shading	Glazing	Roof Insulation	Natural Ventilation	Lighting System	Cooling Load (kBtu/hr)	Life Cycle Cost (PKR)
Base Case	None	None	None	None	None	None	106.3	419,663,026
1	Rock Wool	Original Curve	Low-e#2	R5	Operable Windows	CFL	88.2	337,148,788
2	Rock Wool	Fixed Horizontal	Smart Glass	R5	Operable Windows	LED	84.8	323,385,505
3	Rock Wool	Vertical Louvers	LECLR2	R10	Night Ventilation	CFL	85.3	328,479,962
4	Rock Wool	Egg Crate	HRBLULE2	R10	Night Ventilation	LED	82.6	297,086,844
5	EPS	Fixed Horizontal	Low-e#2	R10	Night Ventilation	CFL	83.1	327,504,968
6	EPS	Original Curve	Smart Glass	R10	Night Ventilation	LED	80.3	301,512,244
7	EPS	Egg Crate	LECLR2	R5	Operable Windows	CFL	78.2	320,718,286
8	EPS	Vertical Louvers	HRBLULE2	R5	Operable Windows	LED	76.3	301,578,429
9	XEPS	Vertical Louvers	Low-e#2	R5	Night Ventilation	LED	84.1	317,064,221
10	XEPS	Egg Crate	Smart Glass	R5	Night Ventilation	CFL	84	325,843,795
11	XEPS	Original Curve	LECLR2	R10	Operable Windows	LED	86	321,392,096
12	XEPS	Fixed Horizontal	HRBLULE2	R10	Operable Windows	CFL	86.2	327,998,734
13	Cellular polyurethane	Egg Crate	Low-e#2	R10	Operable Windows	LED	79.9	295,307,900
14	Cellular polyurethane	Vertical Louvers	Smart Glass	R10	Operable Windows	CFL	80.5	308,298,556
15	Cellular polyurethane	Fixed Horizontal	LECLR2	R5	Night Ventilation	LED	80.1	295,955,660
16	Cellular polyurethane	Original Curve	HRBLULE2	R5	Night Ventilation	CFL	81.1	303,464,046

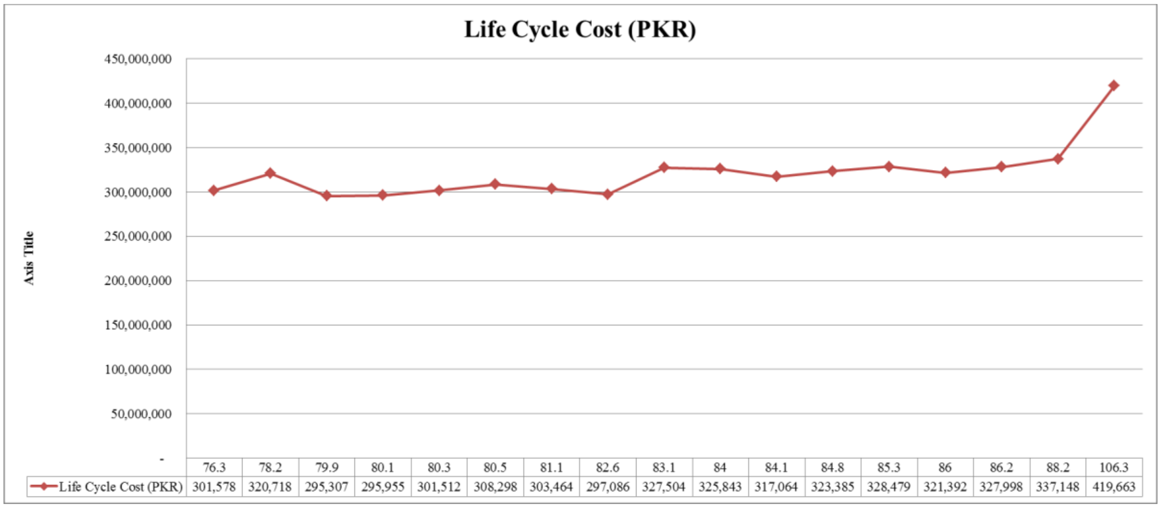

Figure 4-4: Cooling load vs. LCC

The selection of optimum combination of strategies cannot be solely based on one outcome therefore the combined effect of cooling load and LCC for each scenario was calculated by assigning 50% weightage to each output and ranked in the ascending order as shown in Table 10 and Fig. 4-5.

Table 9: Combined effect of cooling load and LCC

Scenario	Cooling Load (kBtu/hr)	Life Cycle Cost (PKR)	Total Score
13	79.9	295,307,900	147,653,990
15	80.1	295,955,660	147,977,870
4	82.6	297,086,844	148,543,463
6	80.3	301,512,244	150,756,162
8	76.3	301,578,429	150,789,252
16	81.1	303,464,046	151,732,063
14	80.5	308,298,556	154,149,318
9	84.1	317,064,221	158,532,152
7	78.2	320,718,286	160,359,182
11	86	321,392,096	160,696,091
2	84.8	323,385,505	161,692,795
10	84	325,843,795	162,921,940

5	83.1	327,504,968	163,752,526
12	86.2	327,998,734	163,999,410
3	85.3	328,479,962	164,240,024
1	88.2	337,148,788	168,574,438
Base Case	106.3	419,663,026	209,831,566

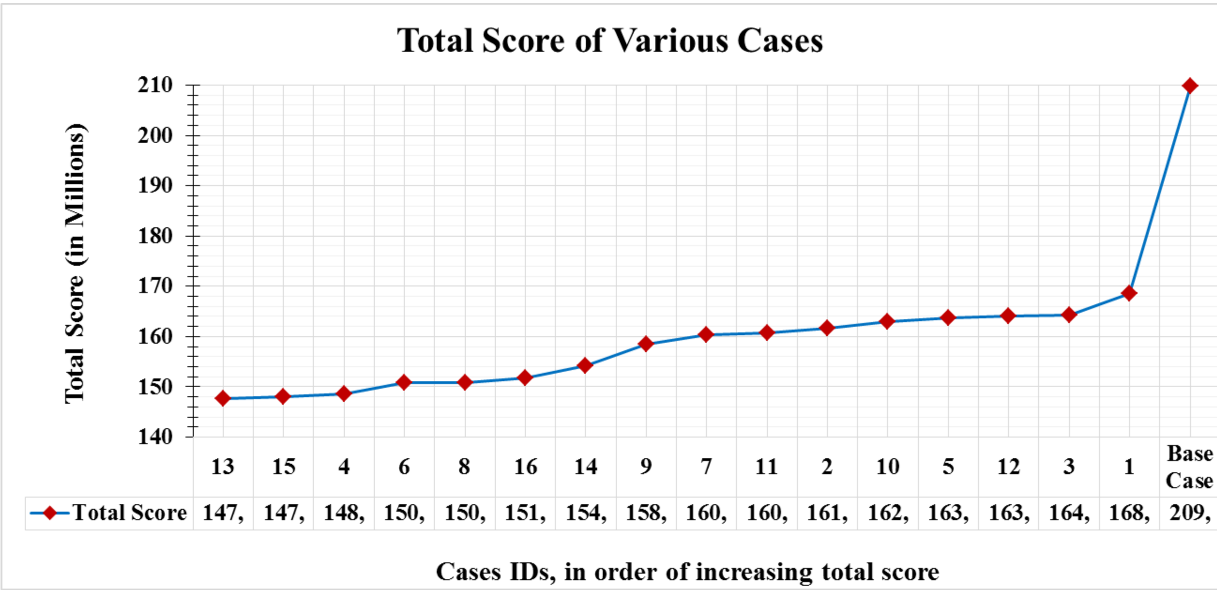

Figure 4-5: Combined score in increasing order

Total score shows that the Scenario 13 has the best overall performance with a significantly reduced cooling load of 79.9 kBtu/hr and the minimum LCC value of PKR 295,307,900 (US$ 2024390), resulting in 24.84% reduction in cooling load and 29.63% reduction in LCC. It is closely followed by Scenario 15 with 24.65% reduction in cooling load and 29.47% reduction in LCC. Both the configurations have same external wall insulation and lighting systems but differ in shading, glazing, roof insulation and natural ventilation. The capital cost of Scenario 15 is marginally lesser than Scenario 13. However, its operating cost increases due to the increased energy cost ultimately resulting in slight increase in overall LCC of Scenario 15, leaving Scenario 13 as the best optimum combination of strategies.

Conclusion and recommendations

In the present study, a comparison of 16 scenarios by evaluating the performance of a residential building located in Lahore, Pakistan (hot semi-arid climate) using different cooling load reduction strategies has been performed. Life cycle cost of each scenario was investigated to strengthen the comparison. The combined effect of cooling load and LCC shows that Scenario 13 comprising of cellular polyurethane for external wall insulation, egg crate shading as an external shading device, soft coated low-e glass for windows, fiberglass (R-10) as roof insulation, cross ventilation through windows and LED lighting system proved to have the best performance with a significantly reduced cooling load of 79.9kBtu/hr (24.84%) and minimum LCC value of 295,307,900 PKR (29.63%).

The results offer quantitative information useful for decision makers, architects and planners by comparing different passive and active cooling techniques alternatives. It is recommended to opt utilize the strategies grouped in Scenario 13 to achieve a reduced cooling load and LCC of a residential building throughout its life cycle. The implementation of the proposed strategies not only aids in providing a user-friendly decision making, it also promotes the adoption of sustainability in buildings by enhancing the environmental and economic aspects of the subject building. This is a promising approach to ease the implementation of green building construction in the developing countries.

Considering the time constraint and availability of data, this study was restricted to cooling load reduction strategies for residential buildings based on only one climate; hot semi-arid. The accuracy of LCC is based on the cost variables used. The energy consumption for the proposed model was calculated using the software. However, with the availability of information about actual building performance, estimated LCC can be updated accordingly. It would be of interest to explore and analyze the combination of passive and active strategies along with their cost analysis with divergent climatic ranges for future studies. Moreover, heating design optimization can also be proposed for heating dominant areas.

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