GREEN ROOF DESIGN AND PRACTICES:
A CASE OF DELHI

A thesis submitted to the
College of Architecture and Environmental Design
of Kent State University in partial fulfillment of the requirements for the degree of
Masters of Architecture

By
Rohini Srivastava
August 2011
TABLE OF CONTENTS

TABLE OF CONTENTS ................................................................. iii

LIST OF FIGURES ........................................................................ vi

LIST OF TABLES ........................................................................ ix

ACKNOWLEDGEMENTS .............................................................. x

CHAPTER

1. GREY TO GREEN: A STRATEGY FOR DELHI ............................. 1
   1.1 Prelude ............................................................................. 1
      1.1.1 Indian Architecture ..................................................... 2
      1.1.2 Green roofs – a sustainable Practice for Delhi ............... 6
      1.1.3 Office buildings ......................................................... 7
   1.2 Problem Statement .......................................................... 9
   1.3 Objectives ...................................................................... 10
   1.4 Method ........................................................................ 10
   1.5 Scope ........................................................................... 11

2. AN INTRODUCTION TO GREEN ROOFS ................................. 14
   2.1 Introduction ................................................................... 14
   2.2 Background ................................................................... 14
      2.2.1 History of Roof Gardens ............................................ 15
      2.2.2 The Development of Green Roofs ............................... 17
      2.2.3 Contemporary use .................................................... 18
   2.3 Green Roof Systems ..................................................... 20
   2.4 Green roof system components ....................................... 23
      2.4.1 Structural Layer ....................................................... 23
      2.4.2 Growing Media ....................................................... 27
      2.4.3 Vegetative Layer ..................................................... 27
   2.5 Benefit of a green roof installation ................................. 28
      2.5.1 Storm water runoff management ............................... 29
      2.5.2 Mitigation of Urban Heat Island ............................... 30
      2.5.3 Habitat restoration and wildlife preservation ............. 31
      2.5.4 Roof life longevity .................................................. 32
      2.5.5 Aesthetic pleasure .................................................. 34
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>The Jagadambi Temple, Khajuraho</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>Lingaraj Temple, Bhubaneswar</td>
<td>2</td>
</tr>
<tr>
<td>1.3</td>
<td>Man Mandir, Rajput palace Gwalior</td>
<td>3</td>
</tr>
<tr>
<td>1.4</td>
<td>Diwan-i-Khas, Delhi</td>
<td>3</td>
</tr>
<tr>
<td>1.5</td>
<td>The Victoria Memorial Hall</td>
<td>3</td>
</tr>
<tr>
<td>1.6</td>
<td>A bungalow, New Delhi</td>
<td>4</td>
</tr>
<tr>
<td>1.7</td>
<td>A Bungalow, Ahmedabad</td>
<td>4</td>
</tr>
<tr>
<td>1.8</td>
<td>Chandigarh Capitol Complex</td>
<td>4</td>
</tr>
<tr>
<td>1.9</td>
<td>Gandhi Labor Institute</td>
<td>5</td>
</tr>
<tr>
<td>1.10</td>
<td>The India International Centre, New Delhi</td>
<td>5</td>
</tr>
<tr>
<td>1.11</td>
<td>The Connaught Place area, New Delhi</td>
<td>5</td>
</tr>
<tr>
<td>1.12</td>
<td>Gateway Tower, Gurgaon</td>
<td>5</td>
</tr>
<tr>
<td>1.13</td>
<td>The average daily Heat flow through a vegetated and unvegetated roof</td>
<td>8</td>
</tr>
<tr>
<td>2.1</td>
<td>The section drawing of the Hanging Garden of Babylon</td>
<td>15</td>
</tr>
<tr>
<td>2.2</td>
<td>Roof garden of the papal palace Pienza</td>
<td>16</td>
</tr>
<tr>
<td>2.3</td>
<td>View of Hermitage roof Garden</td>
<td>16</td>
</tr>
<tr>
<td>2.4</td>
<td>Derry and Toms Roof Garden</td>
<td>17</td>
</tr>
<tr>
<td>2.5</td>
<td>Sod house in Gothenberg, Nebraska</td>
<td>18</td>
</tr>
<tr>
<td>2.6</td>
<td>A house in Norway</td>
<td>18</td>
</tr>
<tr>
<td>2.7</td>
<td>MAG Shopping Mall roof</td>
<td>19</td>
</tr>
<tr>
<td>2.8</td>
<td>The School of Art and Design, Nanyang University Singapore</td>
<td>20</td>
</tr>
<tr>
<td>2.9</td>
<td>Illustration of Green roof systems and an overview of their characteristics</td>
<td>21</td>
</tr>
<tr>
<td>2.10</td>
<td>Green Roof Assembly</td>
<td>23</td>
</tr>
<tr>
<td>2.11</td>
<td>Extensive Green Roof System</td>
<td>25</td>
</tr>
<tr>
<td>2.12</td>
<td>Image of a root barrier</td>
<td>25</td>
</tr>
<tr>
<td>2.13</td>
<td>Images of different kinds of drainage matting</td>
<td>26</td>
</tr>
<tr>
<td>2.14</td>
<td>Images of different types of filter fabrics</td>
<td>26</td>
</tr>
<tr>
<td>2.15</td>
<td>Evapo transpiration and Shading on a Green Roof</td>
<td>28</td>
</tr>
<tr>
<td>2.16</td>
<td>Section through a green roof designed showing wildlife benefit</td>
<td>31</td>
</tr>
</tbody>
</table>
5.3 East side elevation………………………………………………………… 77
5.4 View of central court……………………………………………………… 77
5.5 South – West Elevation of TCI office…………………………………… 78
5.6 Comparison of heat balance of roof for TCI building………………… 79
5.7 Comparison of energy consumption of the TCI building……………… 79
5.8 Comparison between the fuel consumption of TCI building………… 81
5.9 Comparison between the chiller electricity load of the TCI building…… 82
5.10 Comparison of the design cooling load for the top most floor of the TCI 83
5.11 Passive techniques used………………………………………………… 85
5.12 Stereographic diagram representing the Direct Solar Radiation…….. 86
5.13 The chosen orientation for the building………………………………… 87
5.14 Study of solar radiation incident on various building configurations…… 88
5.15 Section through the light well highlighting the self shading character…… 89
5.16 Screen protecting the South West façade……………………………… 90
5.17 The section through a green roof………………………………………… 91
5.18 South West Building View showing the screens……………………… 93
5.19 West South Elevation…………………………………………………… 94
5.20 East North Elevation…………………………………………………… 94
5.21 North West Elevation…………………………………………………… 94
5.22 South East Elevation…………………………………………………… 94
5.23 Comparison of Design cooling load…………………………………… 95
LIST OF TABLES

<table>
<thead>
<tr>
<th></th>
<th>The contribution of land cover in residential and non residential areas</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Green roof system attributes</td>
<td>22</td>
</tr>
<tr>
<td>2-2</td>
<td>Influence of substrate depth on rainfall runoff</td>
<td>30</td>
</tr>
<tr>
<td>2-3</td>
<td>Public &amp; private benefits of Green roofs depending on scale</td>
<td>37</td>
</tr>
<tr>
<td>3-1</td>
<td>Identification of best Passive Cooling &amp; Heating strategies for New Delhi</td>
<td>43</td>
</tr>
<tr>
<td>6-1</td>
<td>A comparison of benefit between a green roof and a conventional roof</td>
<td>98</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

I wish to thank my thesis advisor, Dr. Adil Sharag Eldin, for the intellectual support, and creation of an environment of learning and growth, and patience through the course of my studies at the Kent State University.

I would like to extend my gratitude to Prof. Jonathan Fleming for his continued educational support and encouragement from the early stages of this study.

I am thankful to Dr. Oscar Rocha and the Department of Biological Sciences for providing valuable guidance and insight into the biological aspect of this investigation.

Lastly, I am extremely grateful to my parents, family and friends for their constant support during the course of this thesis and my studies at the Kent State University.
CHAPTER 1

GREY TO GREEN: A STRATEGY FOR DELHI

1.1 Prelude

In the Indian culture it is believed that the processes of the cosmos are directly related to the human existence and that influence can be seen in the architecture (Gast, 2007). People have been respectful of their environment for centuries and this integration can be seen in the building tradition. Typical principles include climate responsive design, use of local and sustainable materials, water harvesting and others, all of which have been refined over time. With increase in the development of housing and commercial buildings, designing with the environment is often disregarded leading to immense pressure on energy resources, water, land, air and degradation of the environment.

The ninth Plan of the Government of India attempts to address the issue and stresses the improvement of urban areas as economically efficient, socially equitable and environmentally sustainable entities (Majumdar, 2001). Often this is not achieved, as growth and spread of cities requires the replacement of forests and green areas of the urban center by buildings, concrete roads, and parking lots. Presence of hard surfaces, along with loss of vegetative cover results in alteration of water and air quality, creation of Urban Heat Island, increase in pollution levels and increased energy Consumption (Cantor, 2008). The introduction of vegetation in the urban fabric may help to mitigate these ill effects but space limitations around a building often pose a restriction. Vegetation may be superimposed onto the horizontal and vertical surfaces of the
building. Green roofs and walls respond to this opportunity and can bring green spaces into urban areas while offering thermal benefits and energy savings for the user.

1.1.1 Indian Architecture

Sustainable design techniques and various socio cultural determinants of the nation have contributed to the plurality and unique architecture of India (Gast, 2007). The absence of a centralized rule in ancient India and coexistence of various schools of thought like Hinduism, Buddhism, Jainism shaped the architectural vocabulary (Lopez, 2003). The cave and stone architecture (figure 1.1, 1.2) utilize local materials and were determined by the cosmological connotations, myth and discourse (Gast, 2007).

With the coming of the Persians in the 7th Century A.D much of that changed and a sense of opulence and ostentations marked the building practices (Cooper & Dawson, 1998). This continued until the Mughal period and the emergence of a new movement called the Indo Islamic style. The architectural style incorporated Islamic and pre Islamic expression into the architectural vocabulary (Evenson, 1989). An example of this is the Moghul Emperor Akbar’s city of Fatehpur Sikri, where vernacular expressions were
adapted into Islamic vocabulary as a climate responsive strategy. The inclusion of deep overhangs (figure 1.3), courts (figure 1.4) and water bodies helped achieve a cooling effect (Lopez, 2003).

Figure 1.3: Deep overhang overlooking the courtyard of Man Mandir, Rajput palace Gwalior (Tillotson, 1990)  
Figure 1.4: The shaded interiors of the Diwan-i-Khas, Delhi overlooking the court (Tillotson, 1990)

The arrival of the European colonialists in the 17th century coincided with the decline of the Mughal era and revival of Hinduism (Gast, 2007). The architecture became a statement of imperial power with its grandeur and stylistic elements borrowed from the Christian religion and European Classicism. Modern thought, brought by the British, included a new vocabulary of materials, technology, methods and processes. Construction during this time was an adaptation of the Indian form in the colonial works brought from Europe (figure 1.5) (Evenson, 1989).

Figure 1.5: The Victoria Memorial Hall (now National Art Gallery), Chennai contains elements from the Indian and colonial styles (Lang, et al., 1997).
In major centers like Delhi colonial domestic and administrative building incorporated the Graeco Roman classical tradition with the north Indian Haveli. The Anglo-Indian style was used for government offices, schools, colleges and the bungalow (Evenson, 1989). The distinct Bungalow architecture (figure 1.6, 1.7) developed as a response to hot climate of the region. By integrating covered verandahs of the traditional house into the Bungalow private courtyards transformed into semi-public verandah for summer cooling.

Post independence Le Corbusier’s design for the city of Chandigarh (figure 1.8) became the symbol of modern Indian architecture and exploration for a national identity. The climate responsive principles like extended overhangs and deep recesses lent a new architectural vocabulary.
In the 1980’s, modernism expressed the realities of Indian society. Many architects felt it needed to be appropriated to the Indian context. Practitioners like Charles Correa, Balkrishna Doshi, J.A Stein (figure 1.9,1.10) attempted to incorporate ‘Indianess’ into modern architecture to bring about ‘modern Indian architecture’ (Gast, 2007).

Figure 1.9: Gandhi Labor Institute by B.V Doshi (Lang, et al., 1997)  
Figure 1.10: The India International Centre, New Delhi by Stein(Lang, et al., 1997)

In 1991, the liberalization of the economy influenced urban Indian architecture (Gast, 2007). The Indian economy was allowed to integrate with global realities and demand, supply and profitability became the determinants of architecture. Economic globalization and the affluence of the industrialists translated into glass and aluminum facades (figure 1.11, 1.12) with universalized expressions of corporate and retail buildings leading to unsustainable building practices. Indiscriminate use of glass led to greater reliance on mechanical air conditioning and energy consumption. Leading to inclusion of concepts of sustainability and energy efficient building design, that trend continues today.

Figure 1.11: The Connaught Place area, New Delhi (author) Figure 1.12: Gateway Tower, Gurgaon
1.1.2 Green Roofs – a Sustainable Practice for Delhi

Green building initiatives have popularized the use of green roofs as a strategy to minimize the negative environmental impact of buildings on ecosystems. Green roof is an environmental, social and economical use of the building roof. Green roofs may be installed at any height with an access provided for its maintenance. The planted spaces, may be used to provide human enjoyment and environmental enhancement or energy savings for the users (Osmundson, 1999).

Green roofs which are also known as eco roofs, planted roofs or vegetated roofs may be beneficial for an individual building or a number of buildings at the urban scale, due to the various benefits they offer. Vegetated roofs shade and prevent incoming solar radiation from reaching the structure below (Castleton, Stovin, Beck, & Davison, 2010), regulate the internal climate of the building by insulating it against extremes of climate (Niachou & al, 2001), and provide a cooling effect through evaporation of water from its vegetative and soil surfaces (Barrio, 1998). By reducing the heat flux through the roof, cooling load and energy consumption of the building may be lowered, leading to monetary savings for the owner.

At the urban scale, green roofs reduce the impact of urbanization, through filtration; purification of air and percolation of moisture (Cantor, 2008). One study used computational modeling technique to estimate this thermal benefit. It was estimated that green roofs if placed on 50-60% of rooftops in densely populated cities may reduce the summertime temperature substantially (Luckett, 2009). Cooler cities during peak demand hours help reduce energy consumption and lower carbon emission levels (Weiler & Barth, 2009).
As rooftops make up a significant percentage of the reflective, non vegetated surfaces in cities (table 1-1) (N. Dunnett & Kingsbury, 2008) and because green roofs utilize these areas, their impact may be substantial in Delhi, the eighth largest metropolitan area in the world (United Nations, 2009). Vegetated roofs may introduce green areas into urban areas that would otherwise be devoid of greenery.

**Table 1-1:** The contribution of roof, pavement and vegetation land cover in residential and non residential areas (Chicago, Houston, Salt Lake City and Sacramento) from Wong (2005)

<table>
<thead>
<tr>
<th></th>
<th>Residential areas</th>
<th>Non residential areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roofs</td>
<td>21-26%</td>
<td>21-24%</td>
</tr>
<tr>
<td>Pavements</td>
<td>28-32%</td>
<td>37-52%</td>
</tr>
<tr>
<td>Grass</td>
<td>30-43%</td>
<td>11-24%</td>
</tr>
<tr>
<td>Other</td>
<td>6-16%</td>
<td>10-17%</td>
</tr>
<tr>
<td>Trees</td>
<td>11-22%</td>
<td>4-12%</td>
</tr>
<tr>
<td>Total roof+pavement</td>
<td>50-56%</td>
<td>60-71%</td>
</tr>
<tr>
<td>Total grass+trees</td>
<td>48-54%</td>
<td>16-30%</td>
</tr>
</tbody>
</table>

The climate of Delhi also provides an opportunity to benefit from the cooling properties of the green roof which are greatest in hot climates when the rate of evaporation is highest. The energy savings and financial advantage from lower energy bills, apart from the addition of green spaces into dense urban areas make green roofs a favorable passive cooling strategy for Delhi.

1.1.3 Office buildings

When green roof design is considered for office buildings, Vegetated roofs may serve a variety of functions and range of users. Planted roofs at the individual and the organizational level may become places of recreation for the executives and workers and areas for the entertainment of clients. Green roofs provide a unique identity to the office by serving as visual amenities that detract from roof views (Osmundson, 1999). The increase in workforce and improvement of office space design, the workspace may accommodate for areas where users may relax and recharge with the visual assistance.
Plants on the roof make use of the sun’s energy which keeps the upper floors cooler and lowers outer surface temperatures and heat gain through the roof membrane. A low rise building with a high roof to wall ratio benefits the most from a green roof compared to a high rise building that loses energy through the building envelope and glazing (Weiler & Barth, 2009). Since the cooling effect is greater on buildings with roof exposure or upper floors of taller buildings, internal load dominated buildings can benefit from the thermal load reduction. Medium sized office buildings fall in this category as they have relatively large roof footprints compared to residential units.

By lowering indoor temperatures, green roofs may be able to reduce the energy consumption and air conditioning costs in office buildings. This may be significant for internal load dominated office buildings as they rely on mechanical cooling. In a study by Environment Canada for a typical one storey building with a grass roof in Toronto a 25% reduction in summer cooling loads compared to reference bare roof was observed (figure 1.13) (N. Dunnett & Kingsbury, 2008). Another study at the National research council of Canada over a two year period in Toronto revealed that living roofs were effective in reducing indoor temperature. The daily maximum temperature underneath the green roof was lower than membrane temperature of the bituminous reference roof.

Figure 1.13: The average daily Heat flow through a vegetated and unvegetated roof in Toronto, Canada between January 2001 and December 2001(Nigel Dunnett & Kingsbury, 2008)
A major reason for the popularity of the green roof is the contribution they make to the building insulation and energy savings. The first known study that recognized this thermal benefit of a green roof was carried out in the late 1970s. Research by Prof Hans Joachim Liesecke (at the institute for Green Planning and Garden Architecture, University of Hannover) and by Dr Walter Kolb (at the Bavarian Institute for Viticulture and Horticulture at Vietshochheim) established thermal load reduction, energy conservation and reduction in the rate of storm water runoff achieved by the use of green roofs (N. Dunnett & Kingsbury, 2008). Apart from the thermal advantage, green roof plants purify the air (Peck, 2008) and provide protection to the roof membrane by reducing the direct solar exposure. Planted roofs may also impart a visual character to the building roof and become complementary addition to the fundamentals of office design identified by Kohn and Katz in 1900’s that are relevant today. Through the addition of a green roof the needs of the individual employee, functioning of the organization and the identity of the company within the building may be enhanced (Kohn & Katz, 2002).

1.2 **Problem Statement**

This thesis argues that green roofs play a critical role in reducing energy costs and improving air quality in urban areas. The reduction is achieved by the increase in heat capacity and shade provided to the building roof. The lower ambient temperatures and heat gain through the roof may provide comfort to the occupants as the temperature reduction decreases the need for mechanical cooling.

Past studies on planted roofs have established the thermal benefits in extreme climates by emphasizing the reduction achieved in winter heating (Niachou & al, 2001) and summer
cooling (Kumar & Kaushik, 2005). Theoretical models that relied on the analysis of planted roofs specifically the growing medium (Eumorfopoulou & Aravantions, 1998) and the canopy layer (Barrio, 1998) were used to estimate the cooling effect of green roofs. The lack of experimental data for other climates such as composite climates, make it difficult to evaluate the suitability of green roofs as a heat mitigation strategy for Delhi. An assessment of a green roof’s performance in a composite climate is thus required to quantify the energy savings. Computer simulations can account for the difference in climate and variation in factors affecting the performance. The data collected will assist designers in their future decisions and establish the role of green roof as a passive cooling strategy for the region.

1.3 **Objectives**

The objectives of this study were manifold and a series of simulations were designed to

1. Evaluate the performance of a green roof in composite climate;

2. Establish factors that affect the performance of the green roof;

3. Assess the building energy savings and potential for a green roof retrofit in an existing office building in Delhi

4. Use the findings from the previous sections as guidelines and develop a new office design that had similar area, height and program requirements as the existing office building that was modeled for the green roof retrofit.

1.4 **Method**

The comparison of heat gain and loss represented by the heat balance of a green roof and a reference non vegetated roof was the beginning point for the study that helped establish
the role of green roofs as a heat mitigating strategy for Delhi. Following this, the study was carried out in two steps. In the first step, a thermal evaluation of the green roof based on the factors that affect its performance was conducted. Parameters for evaluation were identified through a literature review and followed up by computer simulations. The modeling was done using EnergyPlus module in Design Builder software. The simulations responded to a change in orientation, building configuration, construction materials and foliage characteristics (height of plants, leaf area Index).

In the second part, architectural applications of green roofs were explored. For this, a vegetated roof was modeled on an existing office building and the energy savings recorded. Analysis of the heat balance of the roof for (1) with the green roof installation and (2) without the green roof, concluded that green roofs alone may not lead to lower heat gains and energy saving, building the case for a new office design. The new design had requirements similar to the existing office (similar floor area, building height) and was designed by incorporating findings from the first phase of the study and passive strategies identified. On the basis of the results, observations guidelines were created for future use.

1.5 Scope
This study is comprised of the evaluation and creation of guidelines for the use of vegetated roofing systems in composite climates. The thesis is divided into three parts; in the first part various green roof systems and their benefits are highlighted. The second deals with the effect of different parameters on the performance of a green roof in Delhi and the last section highlights the architectural application of green roofs in offices.
Chapter 2 introduces the various green roofs concepts and traces their evolution from the ancient past to the present reflecting that green roofs are not a new technology but a part of ancient traditional practices. This chapter also describes contemporary green roof systems and components along with the numerous benefits a green roof installation offers.

Chapter 3 explores possibility of utilizing the thermal benefits of a green roof installation for Delhi. Apart from a basic description of the climate, best passive practices for Delhi have been identified. Through a detailed literature review it was also established that green roofs incorporate passive strategies that are suitable for Delhi.

Chapter 4 discusses the simulation result of green roof systems modeled on a medium size office in Delhi. The effect of varying several parameters such as orientation, building materials, aspect ratio and foliage characteristics on the performance of the green roof was studied and analyzed using the computer software Design Builder.

Chapter 5 demonstrates the architectural application of green roofs. The chapter has been organized through a twofold approach; the first, deals with the application of a green roof on an existing office building. The energy savings and reduction in fuel consumption were noted by modeling a green roof on the existing building. The second, develops guidelines for future use, demonstrated through design of an office building with similar requirements (building program, area and height) as the existing office that was used for the green roof retrofit modeling. The new office plan incorporates the passive practices for Delhi (like a green roofs, shading, addition of thermal mass etc.) to increase the energy savings and demonstrate how building design may impact in a total design approach in lowering the thermal loads compared to the use of green roofs alone.
Chapter 6 concludes the study with the evaluation of the green roof system in a composite climate. It summarizes the findings from the previous section and proposes guidelines for future practice.

Appendix A lists the vegetation that may be used on green roof installation in Delhi.
CHAPTER 2
AN INTRODUCTION TO GREEN ROOFS

2.1 Introduction
Green roofs and roof gardens are terms that are often used interchangeably when referring to a roof that supports vegetation. Professionals, however, draw a distinction between the two types (Werthmann, 2007); roof gardens are installed for the access and enjoyment of people. They are also costly to build, require intensive maintenance and are heavy in weight due to the deep soil profiles. In contrast, green roofs are lightweight with thin soil profiles and minimal maintenance requirements. They are cheaper to construct as they are installed for environmental performance and visual improvement only. The origin of green roofs can be traced back to the vernacular architecture of various regions, while roof gardens have been documented as being built by the affluent class since ancient times (Osmundson, 1999). Both green roofs and roof gardens have influenced the modern day green roofing system.

2.2 Background
For centuries it has been common to use rooftops as a living space and as an extension of the interior. In hot and cold climates vegetated roofs have been a means of protection from the extreme weather (Luckett, 2009). Vegetation on the roof not only provides insulation to the buildings but also additional thermal mass on the roof which offers protection from fluctuations in weather. Soil covered huts in warm climates of Tanzania are known to have reduced summer cooling requirements (Werthmann, 2007) while Northern European countries are protected from the cold (Weiler & Barth, 2009). It was
however, the development of new building materials; construction techniques that encouraged use of greenery on flat roofs.

2.2.1 History of Roof Gardens

The first known historical reference to a roof garden above grade is for the stone temples in the region of Mesopotamia (Werthmann, 2007). Civilizations in Mesopotamia built roof gardens thousands of years ago on the landings of Ziggurats, or stepped pyramids. The plantings of trees and shrubs softened the climb, provided shade and relief from the heat (N. Dunnett & Kingsbury, 2008).

The next known successor to the roof gardens are the Hanging Gardens of Babylon built by the Persians around the 500 B.C (Weiler & Barth, 2009). The roof gardens along with being a visual delight cooled the hot landscapes and provided greenery (figure 2.1).

Figure 2.1 The section drawing of the Hanging Garden of Babylon, circa 500 B.C based on archeologist Robert Koldewey’s description. From ROOF GARDENS: HISTORY, DESIGN, AND CONSTRUCTION by Theodore Osmundson. Copyright © 1999 by Theodore Osmundson. Used by permission of W.W. Norton & Company, Inc.

In the Middle Ages and Renaissance, there were additional demands from the roof gardens and that was to meet the demands of Christian ecclesiastical architecture and wealthy families of the era (Osmundson, 1999). Palazzo Piccolomini, Pienza, Italy (figure 2.2) and the Cloister garden at Mont-Saint-Michel at France are classic examples of roof gardens that remain today (Osmundson, 1999). In Russia, under the czarist rule, roof gardens were considered a luxury by the nobility. Catherine II of Russia (1729-96)
commissioned the famous roof garden on the Winter Palace (figure 2.3) in Saint Petersburg (Osmundson, 1999)

Figure 2.2: Roof garden of the papal palace, Pienza overlooking the river valley
Figure 2.3 The view of the Hermitage roof garden in the Winter Palace

However it was the development of concrete as a roofing material in the mid 1800’s that lead to widespread creation of rooftop gardens. Planners, architects of the time envisioned cities with roof gardens on flat concrete roofs. The World Exhibition in Paris 1867 was one of the first demonstrations of a planted concrete roof in Western Europe (Nigel Dunnett & Kingsbury, 2008). Created by Karl Rabbitz it was considered a breakthrough in addressing issues related to modern day green roof gardens, like waterproofing, drainage (Osmundson, 1999). Thereafter, apartments with planted terraces, gardens and restaurants with roof gardens followed all over the world. Frank Lloyd Wright, Walter Gropius, Le Corbusier further popularized the use roof gardens by using them extensively in their buildings. Corbusier even included them in his five elements towards a new architecture (Werthmann, 2007).

In the twentieth century, use of roof gardens was promoted through the modernist movement. Roof gardens and terraces fulfilled the demand for a habitable outdoor space at the roof level and at the same time alleviated the lack of hygienic green spaces
associated with heavily urbanized areas (N. Dunnett & Kingsbury, 2008). Gardens built in the 1930s like The Derry and Toms garden (figure 2.4) in the Kensington section of London and the gardens atop the Rockefeller Center roof in New York still influence modern roof gardens (Osmundson, 1999).

![Figure 2.4: The Spanish Garden at Derry and Toms Roof Garden. From ROOF GARDENS: HISTORY, DESIGN, AND CONSTRUCTION by Theodore Osmundson. Copyright © 1999 by Theodore Osmundson. Used by permission of W.W. Norton & Company, Inc](image)

By end of the twentieth century, green roofs gained more importance as they offered various advantages over conventional roofs and old buildings could benefit too.

2.2.2 The Development of Green Roofs

The popularity of modern day green roofs can be traced to the European countries where environmentalists, radical groups and scientific research utilized the technology of the time to develop green roof installations. Known to exist for centuries, in form of Sod roofs in Scandinavia, vegetated roofs provided extra warmth and insulation in the cold, wet climate (Snodgrass & McIntyre, 2010). However the susceptibility to leaking, extensive maintenance and frequent replacement, lead to eventual rejection of sod roofs (figure 2.5, 2.6) in favor of new leak proof construction techniques.
Other vernacular examples have been recorded in the traditional houses of tropical regions of China and Japan. The summer rainfall was often damaging for the region, but increase in summer humidity levels supported the growth of vegetation on roofs. Plant roots helped in bonding and strengthening of the structure (Nagase, 2008) and protected the thatch from washing away. Development of modern building materials reduced the number of traditional green roofs as new roof assemblies were cheaper, easy to construct and required less maintenance.

2.2.3 Contemporary use

Contemporary use of green roofs is often attributed to the development of modern building materials and techniques, however the scarcity of land in northern Europe popularized their use (Werthmann, 2007). In late 1960s groups involved in the counter-culture movement of Germany experimented with new ways of living, which can be described as ‘greening the city rooftops’ movement (N. Dunnett & Kingsbury, 2008). Ecologists as well as writers, artists visualized what cities of the future would look like with enormous amounts of greenery. They imagined tower blocks with greenery; flat surfaces planted and plants hanging from balconies, rooftops. This accompanied by
publication of books and articles on roof greening in the early 1970’s, created awareness about the benefits of green roof systems (N. Dunnett & Kingsbury, 2008).

Today green roofs are being installed in many regions of the world depending on the climate, culture and environmental reasons. In Europe where population is densely concentrated, green roofs are designed as recreational open spaces (figure 2.7), in the form of plazas and playgrounds over underground parking garages (Weiler & Barth, 2009). In this regard, Germany has been the center of green roof development throughout the world for a considerable period. The rapid urban development led to loss of vegetative cover in German cities and the green roofs compensated for the loss of landscape. In England, eco roofs are designed to provide habitat for bird species in populated areas (Gedge, 2003). In contrast, green roofs in North America are installed for economical reasons, as a strategy for reducing energy consumption and long term savings for the owner (N. Dunnett & Kingsbury, 2008).

Figure 2.7: A public park on top of a shopping mall; the MAG Shopping Mall roof, Gellingen, Germany (N. Dunnett & Kingsbury, 2008)

In hot humid climate of South East Asia and parts of South America, roof greening is done to mitigate Urban Heat Island Effect (UHI). There is a growing interest in Singapore
(figure 2.8) and Japan for the use of green roofs to overcome UHI and to provide green spaces for the public (Weiler & Barth, 2009). The Japanese government has introduced a requirement that new buildings with more than 10,760 ft² floor space should have 20% of roof covered with vegetation (Nigel Dunnett & Kingsbury, 2008). The introduction of new ordinances has popularized green roof installations. In Mexico, research is being undertaken to counter the environmental problems experienced by Mexico City, one of the largest metropolitan areas in the world (N. Dunnett & Kingsbury, 2008).

Figure 2.8: The School of Art and Design, Nanyang University Singapore. Photograph by Sidonie Carpenter (N. Dunnett & Kingsbury, 2008)

Multiple benefits offered by green roofs make them a favorable passive technique in various geographic locations. Before these benefits may be understood, an understanding of the green roof components and systems will help capitalize on the advantages offered.

2.3 **Green Roof Systems**

Traditional roof gardens restricted the planting to containers and planters or used a layer of ordinary soil spread on the roof (N. Dunnett & Kingsbury, 2008). The contemporary roof greening systems are however much advanced as they use organic matter instead of
soil for the plant growth. The modern green roofs are categorized by the substrate or growing media depth (Table 2-1 and figure 2.9). There are three types of systems - intensive (deep), semi-intensive (moderate depth) and extensive (shallow) (NCRA, 2007). These categories are derived from the contemporary German tradition of green roofs (N. Dunnett & Kingsbury, 2008).

Intensive green roof systems use a wide variety of plant species. Designed to provide access to people, they support a variety of vegetation from trees and shrubs to herbaceous planting and lawns. Soil depth is at least 0.25 meter (10”) to support the various plant species (Fig 2.9 describes the various green roof system along with their characteristics). Saturated weight for intensive green is approximately 244.1 kg/m² (50 lb/sq ft) and varies thereafter (NCRA, 2007). Intensive roofs are maintained on a rigorous level (Weiler & Barth, 2009) and have more organic growing medium.

Semi intensive green roof systems use a combination of plant species that include small shrubs, grasses and herbs and are limited to low slope structure of 2:12 or less (NCRA, 2007). A medium growth layer from 0.15 m (6”) to 0.25 m (10”) is required for plant
propagation. Semi intensive green roof systems require less regular maintenance than an intensive system but are limited in plant selection due to shallower soil depths. Their saturated weights start at 170.9 kg/m² (35 lb/sq ft) and vary from there.

Extensive roofs are green roofs that are not meant for recreational use, but are intended to be ‘ecological’. Such green roofs provide greenery on the building roof and help preserve biodiversity at that height by providing natural habitat for plants, birds and insects.

Extensive roofs have a narrower range of plant species limited to herbs, low growing grasses, mosses and drought tolerant succulents such as sedum (NCRA, 2007). Substrate depths are relatively thin between 0.05 m (2”) to 0.15 m (6”) which are significantly lower than intensive roofs (Peck, 2008). Saturated weights for extensive green roof system are approximately in the range of 48.8 – 170.9 kg/m² (10-35 lb/sq ft). Extensive green roofs do not require regular input of resources like water, labor as required by an intensive roof and can be designed for steeper slopes (greater than 2:12) (NCRA, 2007). These systems can often be installed on existing buildings without additional structural costs and alterations, but an engineering analysis of the structure must be performed.

Careful selection of plants and growth medium ensures the success of a green roof installation. Table 2-1 summarizes the characteristics of intensive, semi – intensive and extensive green roof systems based on the green roof components like the growing media and vegetation layer.

Table 2-1: Green roof system attributes. Courtesy of: Green Roofs for Healthy Cities (Peck, 2008)

<table>
<thead>
<tr>
<th></th>
<th>Extensive</th>
<th>Semi- Intensive</th>
<th>Intensive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of Growing Medium</td>
<td>0.15 m or less (6”)</td>
<td>25% above or below 0.15 m (6”)</td>
<td>More than 0.15 m (6”)</td>
</tr>
<tr>
<td>Full Saturated weight</td>
<td>48.8 – 170.9 kg/m² (10-35 lb/sq ft)</td>
<td>170.9 – 244.1 kg/m² (35-50 lb/sq ft)</td>
<td>244.1 – 1,464.7 kg/m² (50-300 lb/sq ft)</td>
</tr>
<tr>
<td>Plant Diversity</td>
<td>Low</td>
<td>Greater</td>
<td>Greatest</td>
</tr>
</tbody>
</table>
2.4 **Green roof system components**

Green roofs consist of both horticultural elements and traditional roofing components. There are three distinct layers in a green roof from the bottom (Barrio, 1998) – elements that provide structural integrity; an engineered growing medium (which may or may not include soil) and the plant canopy (components selected as per particular application).

Figure (2.10) illustrates the various components in a green roof system.

1. **Roof Deck, Insulation, waterproofing**
2. **Protection Layer – root barrier**
3. **Drainage Layer**
4. **Root permeable filter layer**
5. **Growing Media**
6. **Vegetation, Plants**

![Figure 2.1: Green Roof Assembly showing the various layers (Snodgrass & McIntyre, 2010)](image)

2.4.1 **Structural Layer**

The components of the structural layer consist of the roof deck (Snodgrass & McIntyre, 2010); the protection layer to contain the roots and growing medium, while allowing water penetration; a drainage layer and retention layer (sometimes with built in water reservoirs); a root repellant filter layer (made up of filter mats to protect the growth media from moving); along with the waterproofing membrane (Peck, 2008).

*(i) Roof Deck, waterproofing and insulation* - The most important layer on a green roof is its decking, which can be concrete, wood, metal, plastic, gypsum or composite as it
determines whether the structure is capable of taking the load of the green roof (Cantor, 2008). Installation of a green roof requires additional structural support based on the increase in dead and live load (due to the growth medium); additional water retention. Buildings with concrete decks are excellent contenders for green roofs as they can take the additional weight of the green roofs and do not require extra support which is otherwise for waterproofing a metal deck (N. Dunnett & Kingsbury, 2008). A reliable waterproofing layer and insulation on the deck (figure 2.1) contribute towards the success of a green roof installation.

Waterproofing - The primary purpose of waterproofing is to keep the unwanted moisture from rain and condensation away from the structure below. The waterproofing membrane is the primary protective element of the slab and is typically below all the components of a green roof system (figure 2.1) (Weiler & Barth, 2009). There are three major roofing types for roofs – Built up membrane, single ply membrane and Fluid applied membrane (Osmundson, 1999). It is important that selection of waterproofing membrane is in accordance with specification of other components within the green roof system.

Insulation – The roof is the primary location for heat transfer and the insulation restricts the transfer of heat energy through the roof by creating a barrier between spaces of different temperature (Osmundson, 1999). The insulation acts as a thermal break and reduces condensation on surfaces that are exposed to both hot and cold on opposite sides (N. Dunnett & Kingsbury, 2008). Green roof systems add mass and insulation over the structural decking, but cannot replace the insulation because their insulating properties depend upon depth and moisture content of growing medium (Weiler & Barth, 2009).
(ii) Protection Layer - As green roofs contain living and growing materials, a protection layer and a root barrier are one of the most important elements of the assembly (Luckett, 2009). As roots grow they can penetrate the waterproofing membrane and create leak locations. The root barrier (figure 2.12) placed above the membrane ensures that no roots pass through and harm the membrane (NCRA, 2007). A protection course shields the waterproofing membrane from damage after it has been installed.

(iii) Drainage and retention Layer – A drainage course allows moisture to move laterally through the green roof system. It prevents oversaturation, ensures root ventilation and provides additional space for the roots to grow (figure 2.13). It is a porous, continuous
layer over the entire roof surface just above the concrete slab (Snodgrass & McIntyre, 2010). As moisture is essential for successful plant propagation, a moisture retention layer retains or stores moisture for plant growth. It is an absorptive mat and which is typically located above the drainage layer or above the aeration layer (NCRA, 2007).

(iv) **Root Permeable filter Layer** – The filter layer separates the growing medium from the drainage layer and protects the medium from shifting and washing away. This layer restricts the flow of fine soil particles and other contaminants while allowing water to pass through freely to avoid clogging (N. Dunnett & Kingsbury, 2008). They are often made of tightly woven fabric and are in the form of filter cloth or mats (figure 2.14) (Weiler & Barth, 2009).
2.4.2 Growing Media

The growing media or substrate in a green roof should strike a balance between good moisture retention capacity and free draining properties of traditional soil (N. Dunnett & Kingsbury, 2008). It should absorb and supply nutrients and retain its volume over time to encourage plant growth. Traditionally, well drained sandy loam was used as the growing medium for a green roof (Cantor, 2008). Its weight and ability to clog drainage layers and fabric lead to use of organic matter as a growing media. Lighter less rich and more porous mixes than soil reduce weight of the growing medium and save cost of structural support (Snodgrass, 2006).

There are four factors that govern the suitability of a growth media. They are - water holding capacity, degree of drainage, fertility for vegetation and density of the growing media. The growing media should also be able to resist heat and other factors that damage normal roof (Snodgrass & McIntyre, 2010). As organic content; pH and nutrient levels, weight, porosity, and water retention capacity of the growing media affect the growth of plants (Weiler & Barth, 2009) it is important to select the substrate carefully.

2.4.3 Vegetative Layer

The selection of appropriate plants is essential to both the aesthetic and environmental function of the green roof. There are various planting propagation methods like pre cultivated mats, modular systems, plugs, cuttings and seeds, all of which vary by cost and type of coverage desired (Earth Pledge, 2005). Selection of plants requires consideration as traditional rules for ground level plant selection do not work on green roofs due to the environmental and geographical location. Microclimate conditions on the roof like sun, shade and wind patterns which do not affect the ground gardens influence the growth of
plants on the rooftop (Earth Pledge, 2005). Thus, plant variety needs to be tougher and less nutrient reliant than ones on the ground (Snodgrass & Snodgrass, 2006).

Plants cool the air around the rooftop through evapo-transpiration (figure 2.15) and shading from the plant cover. Evapo-transpiration is the sum effect of evaporation and plant transpiration from the surface of the vegetation that results in the cooling of the surface as water evaporates from it. Reductions of up to 90% in solar gain on roof area shaded by plant cover compared to un-shaded location can be achieved and indoor temperature decrease of 3-4°C (6-8 °F) may be attained (Peck, 2008).

Designers must select plants according to the zone in which the green roof system is designed to avail all of the benefits vegetated roofs offer.

2.5 **Benefit of a green roof installation**

In addition to the thermal advantage which is the focus of this thesis, there are other advantages of a green roof installation. A green roof is a valuable amenity that enhances the worth of the structure it occupies and generates tangible benefits in the form of financial returns as well as quantifiable environmental benefits. By utilizing wasted roof
spaces multiple objectives may be achieved including storm water management; Urban Heat Island Mitigation; longer life for roof membrane; habitation for urban wildlife and aesthetic value addition etc.

2.5.1 Storm water runoff management

Storm water runoff contains pollutants and contaminants which it picks from conventional roofs, paved areas and roads. In urban areas precipitation cannot permeate through buildings, asphalt and concrete surfaces, therefore contaminated storm water often joins existing rivers, streams and sewer lines instead of percolating through soils. The increased quantity of runoff during storms overburdens the sewerage system leading to its failure (Weiler & Barth, 2009). It may also increase the chances for flooding as the amount of storm water exceeds the capacity of the drainage channel, increasing chances of property and human damage.

Green roofs can be valuable assets that may help to mitigate water runoff problems by lowering the rate of surface runoff. This is especially useful in urban areas with combined storm and sanitary sewer systems. The absorption of rainwater by planted spaces also reduces the chance of the storm water from getting contaminated by pollutants, dust etc. Vegetated roofs moderate the peak in runoff from rooftops in most of the cases except for intense storms. Even during intense storms, lower rate of runoff is recorded compared to a conventional roof (N. Dunnett & Kingsbury, 2008).

At Portland, Oregon two years of storm water management study concluded, green roofs with 0.04 m of substrate retained as much as 69 percent of all rainwater falling on it, with 100 percent retention for most warm weather storms (Hutchinson, Abrams, Retzlaff, & Liptan, 2003). Another study conducted in Belgium showed that water retention
increased with increase in substrate depth and presence of vegetation (Mentens, Raes, & Hermy, 2003). Table 2-2 presents runoff data for different types of roof collected during the study, highlighting the relation between substrate depth and runoff percentage.

Table 2-2: Influence of substrate depth and vegetation on the percentage of total rainfall running off a roof. (Mentens, et al., 2003)

<table>
<thead>
<tr>
<th>Roof type</th>
<th>Runoff(m)</th>
<th>Runoff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>0.66</td>
<td>81</td>
</tr>
<tr>
<td>Standard with 0.05 m of gravel</td>
<td>0.63</td>
<td>77</td>
</tr>
<tr>
<td>Green roof with 0.05 m of substrate</td>
<td>0.40</td>
<td>50</td>
</tr>
<tr>
<td>Green roof with 0.10 m of substrate</td>
<td>0.36</td>
<td>45</td>
</tr>
<tr>
<td>Green roof with 0.15 m of substrate</td>
<td>0.32</td>
<td>40</td>
</tr>
</tbody>
</table>

A decrease in volume and rate of runoff into the drainage system reduces the pressure from the treatment system and the bodies of water in which the system discharges the runoff (Snodgrass & McIntyre, 2010) and green roles may help achieve this.

2.5.2 Mitigation of Urban Heat Island

The loss of vegetative cover and increase in building activity in the form of pavements, roads and buildings results in higher urban temperatures than the suburban and rural areas. As impervious surfaces tend to be heat absorbing structures they increase urban temperature. This specific urban phenomenon termed as the Urban Heat Island Effect (UHI) (Solecki, et al., 2005), is identified by higher night time temperatures and humidity. To cope with this heat, air-conditioning is required which can burden the electric grid during peak hours, adding on to the UHI (N. Dunnett & Kingsbury, 2008).

As rooftops make up a significant percentage of the reflective non vegetated surfaces in the city, heat gained through roofs can be substantial. Introduction of greenery through green roofs in the urban areas can reduce impervious surfaces and soften streetscapes. Plants use heat energy for evapo-transpiration to achieve a cooling effect. By reducing
the heat gain through the roof ambient temperature is lowered leading to less energy consumption (Earth Pledge, 2005). It is estimated that a decrease in internal building temperature by 0.5°C may reduce electricity consumption for air conditioning (which is dependent on the building mass, volume and internal load profile) by up to 8 percent (N. Dunnett & Kingsbury, 2008). Green roofs may be beneficial at night time also, as they radiate less amount of heat as compared to a dark or hard surface.

Green roof is effective at reflecting solar radiation and reducing heat absorption when compared to a conventional roof (N. Dunnett & Kingsbury, 2008). Reduction of UHI is difficult to quantify as large area of green roofs are required to make a substantial impact. Studies show that implementation of green roofs at a large scale in urban areas can have a significant impact on the reduction of UHI through lower air temperatures.

2.5.3 Habitat restoration and wildlife preservation

In urban areas where green spaces are lost at the ground level due to construction activities, green roofs are a means of supporting greenery at the roof level. They can sustain semi natural plant communities, create healthy, functioning habitat for certain kind of wildlife (N. Dunnett, et al., 2007). As extensive roofs are not designed to be accessed (figure 2.16) they are isolated from people, and can be undisturbed habitat for plants, birds and insects (N. Dunnett & Kingsbury, 2008).

Figure 2.7: Section through a green roof designed for wildlife benefit, showing a variety of substrate types and depth (N. Dunnett & Kingsbury, 2008)
Habitats that are otherwise endangered in urban or rural regions may be conserved in these locations. Studies from Europe on mature green roofs suggest that if green roofs are properly designed, needs of birds and insects may be accommodated on those roofs. They can play a pivotal role in preserving urban biodiversity for example in United Kingdom, extensive green roofs are a part of the London biodiversity Partnership’s action plan to restore bird population (Snodgrass & McIntyre, 2010). In the North America green roofs are designed to attract endangered species (figure 2.17) (Coffman & Waite, 2009).

Research indicates that high level of diversity may be achieved on extensive green roofs. The ability of green roofs to support biodiversity is being explored alongside the thermal and hydrological studies but results are still in the nascent stage. If designed well green roofs can become a part of the functioning habitat and green space network of the city.

2.5.4 Roof life longevity

One of the major benefits of green roofs is their contribution in prolonging the life of both building insulation and roof surfaces (Weiler & Barth, 2009). Plants and the growing media of the green roof moderate the temperature on the roof and protect the roof’s waterproofing membrane. It shields roofing materials from ultra violet rays and
higher temperature variation which cause degeneration of insulation and roofing felt. Direct sun causes expansion and contraction of the membrane, thereby weakening it. It also accelerates aging in bituminous materials and reduces their durability.

Exposed roof membranes absorb solar radiation during the day which raises its temperature. The rise in temperature is dependent on the color of the membrane; a light colored membrane is cooler as it reflects solar radiation. Figure 2.18 illustrates the rise in temperature in black, white and a green roof. Other studies also show that exposed roofs experience higher temperatures than green roofs. For example in a study for the city of Toronto, Canada membrane on the non green roof reached close to 70°C (158°F) in the afternoon while the membrane in green roof remained around 25°C (75°F) (N. Dunnett & Kingsbury, 2008). The membrane on a conventional flat roof, if not protect by insulation, must be replaced every fifteen or twenty years (Luckett, 2009). In direct contrast, membranes under green roofs may remain intact after decades of use (Snodgrass & McIntyre, 2010).

![Figure 2.18](image)

Figure 2.18: Graph illustrating the surface temperature fluctuations on a green roof, a reflective white roof, and an unprotected black roof between 5 and 9 June 2008. On hot days, temperature on green roof remains cooler than white roof and a black roof (Werthmann, 2007)
2.5.5 Aesthetic pleasure

Green roofs can play an important role in providing recreational spaces in urban regions where there is little ground level green areas. As these spaces are visible from many vantage points, it adds to the visual character of the urban fabric (Werthmann, 2007). Green roofs that are accessible to the public or private owners add to the enjoyment of the property and provide more interest for the people living or working in neighboring high rise buildings, adding color and texture (Getter & Rowe, 2006).

With the move towards compact and high density cities, there is immense pressure on green spaces at the ground level and high cost of acquisition for ground space makes it difficult to plan for ground level green areas. Roof spaces are highly underutilized resources in urban and suburban areas and have enormous potential in providing urban dwelling with recreational space (figure 2.19) (Earth Pledge, 2005). Recreational spaces at the roof level have controlled access making them safe from vandalism and other social problems common in public green spaces at ground level (Weiler & Barth, 2009).

![Figure 2.19: Roof gardens provide outdoor space that is away from noise & pollution (N. Dunnett & Kingsbury, 2008)](image)

The provision of roof gardens, filled with greenery rather than paved surface, may become a positive selling point for the developers in future.
2.5.6 Food production

Roof surfaces offer the opportunity for growing food, particularly in high density urban areas where garden space may be limited (figure 2.20). Food producing plants can substitute for ornamental plants in conventional roof gardens. Herb species are also known to perform well in free draining soils of extensive roofs and may become a viable option (Earth Pledge, 2005). In Haiti, Colombia, Thailand, Russia rooftops have been used to produce a range of fruits and vegetables (N. Dunnett & Kingsbury, 2008).

![Image: Earth Pledge Kitchen Garden, midtown Manhattan. The green roof is planted with over sixty species of sedum, flowers and edibles like tomatoes, alpine strawberries etc (Earth Pledge, 2005).](image)

Weight bearing capacity of the roof is a consideration for the successful plant growth. Soil depth of 0.3 – 0.45 m (12-18”) may be required along with frequent irrigation (Weiler & Barth, 2009). One of the examples of green roof food production is the Fairmont Hotel in Vancouver, Canada. The garden provides for all the herbs requirements of the hotel thereby making a yearly saving of Canadian $25,000-30,000. Apart from the food they also provide outdoor recreational space for the guests (Weiler & Barth, 2009). The use of roof space for food production is still a new concept, but may become a commercial possibility in the future as no additional land purchase cost is associated with food production.
2.5.7 Acoustic benefits

Hard surfaces of urban areas reflect sound and are unable to absorb it. Green roofs due to the nature of substrate and vegetation absorb sound waves (Getter & Rowe, 2006). They are beneficial in two ways; they provide sound isolation due to the high mass and low stiffness and to a lesser extent reduce noise pollution through surface absorption (Connelly & Hodgson, 2008). The depth of the green roof assembly acts as a acoustical barrier, the substrate blocks lower sound frequencies while the plants stop the higher frequency (N. Dunnett & Kingsbury, 2008) thereby reducing noise of traffic, airplanes.

In a study at the Frankfurt airport, Germany a 0.10 m (4”) deep green roof was able to reduce noise levels by 5dB (N. Dunnett & Kingsbury, 2008). The installation of a green roof atop Gap’s office in California which is situated next to a freeway and airport was designed to dampen noise transmission (Burke, 2003).

2.5.8 Healthy work environment and Amenity value

Cooler temperatures on green roofs in hot weather makes them a valuable outdoor space for people who live or work in the building below (Snodgrass & McIntyre, 2010). Green roofs act as recess spaces in offices where people come and relax during break time and connect with the outdoors. In residential units green roofs help in improving the quality of life for the residents, as they provide spaces for recreational activities. In an observation in Portland, of the various activities that could be performed on green roofs atop apartment blocks, exercise, barbecuing, lounging were most popular (N. Dunnett & Kingsbury, 2008). In urban areas this may be the only outdoor space for people to use, and an extensive roof with sedum designed with landscaping elements like stepping stones, patio may make it a multifunctional low cost roof garden.
2.6 Conclusion

The loss to natural habitats and the ill effects associated with rapid expansion of built environment may be minimized by installation of green roofs. Ecoroofs are one of the few passive techniques that accomplish multiple goals simultaneously. Apart from the energy reduction benefit at the private or small scale level, green roofs also add to the aesthetic value of the property. At the large urban or public scale, green roofs act as the link between private spaces of the built environment, and the public spaces surrounding the site and community while achieving storm water runoff rate reduction, UHI mitigation, biodiversity and habitats. Table (2-3) categorizes the green roof benefits by assigning them economic, social, environmental and aesthetic values.

Table 2-3: Public & private benefits of green roofs depending on scale of the development

<table>
<thead>
<tr>
<th>Scale of development</th>
<th>Values associated with the Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Private Development</td>
<td>Economic</td>
</tr>
<tr>
<td>(apt/single family dwelling)</td>
<td>Reduction in energy costs</td>
</tr>
<tr>
<td>Public Development</td>
<td>Reduction in energy costs</td>
</tr>
<tr>
<td>(Institutional, Municipal infrastructure, Industrial and Ecological)</td>
<td>Lower air pollution thus health benefits for users</td>
</tr>
<tr>
<td></td>
<td>Protection from UV radiation</td>
</tr>
</tbody>
</table>
Since the benefits of green roofs operate at a range of scale, some advantages may be gained only if relatively large numbers of green roofs are implemented and their effect will be apparent at the larger neighborhood or city scale. Based on the scale of the project value to the green roof benefit may be attached.

As residential and nonresidential roofs represent up to 21% to 26% of urban surfaces, they provide an opportunity to reclaim unused spaces. By developing a battery of tests and simulations, the viability of green roof in particular situation may be assessed. This information would assist firms and designers in making the best decision and optimizing the green roof benefits.
CHAPTER 3

THERMAL BENEFIT OF GREEN ROOFS- A CASE FOR DELHI

3.1 Thermal benefits of green roof

Green roofs in urban areas offer a building and its surrounding environment many benefits. Apart from improving the performance of the roofing system through shading, insulation, evapo-transpiration and additional thermal mass it also cools the environment. It regulates the temperature through the year by reducing the heat gain and loss from the building. Lower gains through the building roof lead to lower energy consumption and if widely adopted green roofs can benefit the urban environment of Delhi.

3.2 Green Roofs for New Delhi

Delhi is one of the largest metropolis in the world with more than 12.25 million inhabitants and nearly 22.2 million residents in the National Capital Region urban area (UN, 2009). The demand for new infrastructure and greater energy requirement often leads to chaotic building activities and an unsustainable development. Escalated land prices and shortage of vacant parcels of land in the capital contribute to this and make planning for open vegetated spaces and parks difficult.

Green roofs present an opportunity to bring green spaces into the city, lower the ambient heat island effect and subsequently reduce the outdoor temperatures and heat gain through the building. A number of studies have examined the potential energy savings from using green roofs on buildings for extreme climates. The energy savings are however dependent on the climate, location and the solar radiation incident, that govern heat gain through the building envelope.
3.2.1 Climate of Delhi

North India is dominated by the Gangetic plain covering 359400 sq km, which is one of the most fertile lands in the world (Oliver, 1997). This area is bound by the Himalayan ranges to the north, the Deccan plateau in the south, the Thar Desert and the dry plains of Rajasthan and Haryana in the west. The climate can be classified as composite or monsoon type. Delhi (28° 53’ N latitude) belongs in this zone and has a distinguishable hot, dry period of almost three months, a colder period of a shorter duration and an in between hot humid, monsoon season of about two months (figure 3.1).

Figure 3.1: Map of India showing location of New Delhi (IMD, 2011)

Summers start in early April and peak in April - June, with average temperatures nearing 32°C (90°F). Monsoon which is the period between the two distinct seasons starts in late
June and lasts until mid-September and with the onset of winters in November. Winters in Delhi are generally mild and average winter temperatures recorded are in the range of 12-13°C (54-55°F) (Oliver, 1997). Figure 3.2 shows the various seasons and average temperature range for Delhi.

![Figure 3.2 Temperature range for Delhi](image)

The India Metrological Department for the period of 1901-2009 noted that annual mean temperature for the country rose by 0.56°C (Figure 3.3) over the period. The annual mean temperature have been above normal since 1990 (normal based on period, 1961-1990) (Attri & Tyagi, 2010). The rise in temperature was significant over northern plains where considerable urban development has been recorded. The rise in temperature was attributed to the high levels of pollution in the region (Attri & Tyagi, 2010). Unsustainable building practices in urban areas have been known to cause pollution and increase in temperature. Inclusion of passive techniques in the building design and use of efficient mechanical systems may help counter this increase. Some of the passive practices that are suited for the climate of Delhi are discussed in the following section.
Figure 3.3: All India annual mean temperature anomalies for the period 1901-2009 (based on 1961-1990 average) shown as vertical bars (The solid blue curve show sub-decadal time scale variations smoothed with a binomial filter) (Attri & Tyagi, 2010).

3.2.2 Best practices

Solar radiation incident on a geographical location governs the heat gain through the building envelope (Davis, 1979). As the solar radiation received is dependent on the altitude and weather, and is the maximum for two broad bands between 15 °N and 35 °S latitude (Konya, 1980) hence each location requires a unique climate based solution. With Delhi in this band, large amount of heat is gained through the building envelope and in the absence of passive design results in greater reliance on mechanical systems. Resistive passive cooling strategies are beneficial for the region during the hot season. Based on Delhi’s climate, various passive techniques have been identified in table 3-1. With high amount of solar radiation incident on Delhi, air conditioning will always be required in the warmer months. However the reduction in the indoor temperatures may help achieve lower thermal loads and energy savings for the building. The design of
window overhangs based on the latitude, operable sunshades (extended in summer, retracted in winters) along with the use of plant materials on walls and roofs (through native plants) can reduce the transfer of direct radiation through the envelope. Use of high mass surfaces and shading of the internal surfaces helps keep the building cool on hot days and dampens the day-to-night temperature swings.

Table 3-1: Identification of the best Passive Cooling and Heating strategies for New Delhi

<table>
<thead>
<tr>
<th>Best Practices</th>
<th>Summer (cooling)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resistive strategies</strong></td>
<td>- Avoid heat gain due to solar radiation and infiltration</td>
</tr>
<tr>
<td></td>
<td>(through shading devices, reflective barriers; vegetation; orientation; building form)</td>
</tr>
<tr>
<td></td>
<td>- Minimize Heat transfer through building envelope, roofs</td>
</tr>
<tr>
<td></td>
<td>(use of thermal mass to retard heat gain; use of shading devices; orientation and form of the building)</td>
</tr>
<tr>
<td></td>
<td>- Reduce moisture: Dehumidification</td>
</tr>
<tr>
<td></td>
<td>- Winter insulation and wind protection</td>
</tr>
<tr>
<td><strong>Promotive strategies</strong></td>
<td>- Evaporation (direct evaporative cooling)</td>
</tr>
<tr>
<td></td>
<td>- Mass effect cooling (Thermal mass through earth contact- direct and indirect earth sheltering)</td>
</tr>
<tr>
<td></td>
<td>- Ventilation (Night time ventilation; solar chimneys; wind towers; wind catchers)</td>
</tr>
<tr>
<td></td>
<td>- Radiation (Radiative roof pond; courtyards; cool ponds)</td>
</tr>
<tr>
<td></td>
<td>- Ventilation Enhance air movements, (Earth air tunnel)</td>
</tr>
<tr>
<td></td>
<td>- Direct Gain systems (Southern Exposure of walls, roof and windows)</td>
</tr>
</tbody>
</table>

Greening the roof is a passive cooling technique that combines a number of the above discussed passive techniques and takes advantage of the different processes. Vegetation on the roof reduces the incoming solar radiation through shading, evapo-transpiration and other physiological processes. The thermal mass of the roof lowers the temperature fluctuations and contributes to the cooling potential of green roofs. The various benefits
apart from the potential energy savings offered by the green roof make it a passive technique that may become part of the urban area.

3.3 **A review of green roof studies**

Investigations have been performed in the past to highlight the success of green roofs in reducing the ambient temperature, heat flux and potential energy savings that may be achieved. Contribution of green roofs in energy conservation can be substantial as building activities account for a large amount of energy consumption. A great portion of which is utilized to maintain the internal building temperatures through mechanical systems (Castleton, Stovin, et al., 2010) and by using a green roof these thermal loads may be lowered. The following section summarizes the various studies that have been carried out to assess the thermal benefits of green roofs highlighting the various passive cooling principles they use.

3.3.1 **Mass Effect Cooling**

Del Barrio (1998) explored the thermal behavior of green roofs through mathematical analysis to assess the summer cooling potential of green roofs in Athens, Greece. Through the study of heat and moisture transfer in soil and radiant heat exchange in the canopy layer, it was established that green roofs reduce the heat flux through the roof and act as insulation devices (Barrio, 1998). Through the study it was established that the thickness of the soil layer, its relative density, along with moisture content influences the thermal benefits of the soil layer. It was also concluded that the air pockets in a less dense soil leads to an increase in insulating properties and reduction in soil moisture content contributes to an increase of heat flux through the roof.
In another outdoor experimental setup at Athens, Niachou et al (2001) explored the thermal properties and energy performance of a green roof by measuring surface, air and internal temperature for two buildings. The roofs of the two buildings had similar insulation properties but one had a green roof and the other did not. In the investigation, field measurements were taken during the first phase and in the second thermal properties and energy savings were modeled mathematically. It was found that without the green roof the internal air temperature exceeded 30°C (86°F) for 68 percent of the period, but with the green roof this percentage was reduced to 15 percent (Niachou & al, 2001). Using the simulation program Transient System Simulation Program (TRNSYS) thermal insulation of the green roof installation was varied and a reduction in energy consumption observed. These savings were little for well insulated buildings compared to non insulated buildings.

3.3.2 Reduction of heat flux

There are various advantages of using green roofs in hot climates. They can reduce the heat flux through the roof and these benefits have been explored for the tropical climates in a study conducted by Wong et al (2003). The field experiments were conducted on a roof top in Singapore where the temperature at various depths of green roofs was recorded. A variety of plants were used for the experiment and the authors were able to calculate the thermal resistance of each plant. The thermal effects of a green roof were further evaluated by calculating the heat flux through different types of roofs - bare hard surface, bare soil, turf, tree, and shrub. Along with shading, plants lowered the surface temperature of the roof. A decrease of up to 30°C was recorded on a vegetated roof, which varied according to the foliage density of the vegetation (Wong, Chen, Ong, & Sia,
2003), confirming that it is much cooler on a green roof than a hard surface. The high density of leaves ensures greater surface area for evapo-transpiration which results in more ambient cooling.

The daily maximum temperature underneath the green roof was found to be significantly lower than the daily maximum membrane temperature of the bituminous reference roof in the research conducted by the National Research Council of Canada for the city of Toronto. Green roofs were effective in reducing heat transfer through roof (Weiler & Barth, 2009) and during the 660 day monitoring period the temperature of the green roof exceeded 30°C only on 18 days or 3% of the study duration. The temperature of the reference roof was significantly higher and climbed above 50°C on more than 219 days or 33%. Green roofs reduced the temperature fluctuation in the roof membrane by 5–7 °C throughout the year (Liu & Baskaran, 2003) establishing their cooling potential.

3.3.3 Evaporative cooling effect

A decrease in surface temperature by around 30-60° C on site was noted in a field measurement carried out during the summer months on a planted roof in Japan. Through simple calculations, this reduction was estimated to lower the heat flux into the room below by 50%. This reduction was attributed to the evaporative cooling effect of vegetation on green roofs. The reduction in heat flux was obtained using field measurements and confirmed by a wind tunnel experiment (Onmura et al, 2001). The experiment and field results matched closely, proving that the cooling effect of green roofs was indeed due to the evaporative cooling and thermal capacity of the layer.

Lazzarin et al (2005) evaluated the role of evapo-transpiration in achieving passive cooling in a hospital building in North East Italy during the most dry and most wet
periods of the season. Data from the experimental setup was utilized to create a finite
difference model. Through the modeling it was established that dry green roofs reduce
the incoming heat flux by 60% with respect to conventional roofs. Wet green roofs were
further doubled the heat loss through evapo-transpiration compared to dry green roofs.
The existing research is a step towards the assessment of the energy benefits of green
roofs. These findings can guide future enquiries in regions where green roofs are not
common and help their integration of green roofs into the local building vocabulary.

3.4 Green roof study for Delhi

Delhi is growing as a metropolis and the unrestrained urbanization has lead to loss of
natural resources of energy, water and ground cover, hampering eco-friendly habitat
development (Majumdar, 2001). With increased interest in passive techniques and energy
efficient building design, green roofs have been proposed to address the problems
generated by this urbanization. However, the planted roofs and walls are not part of the
local building practices and its construction has not been explored.

Past research on energy performance of green roofs is limited to the summertime effects
in hot and tropical climates. The studies are restricted to certain locations, climates and
species of plants hence, limited in scope. The findings cannot be applied universally and
to popularize green roofs as a passive cooling strategy for Delhi, data for its thermal
benefit should be available for all seasons. An evaluation of thermal performance may be
carried out using field experiments, mathematical modeling or computer simulations.

In the evaluation for thermal performance of green roofs in Delhi, a mathematical model
was created by Kumar et al (2005). The model was designed so that it could be combined
with the building simulation code and through the model it was found that green roofs reduce the indoor temperatures by up to 5.1°C (figure 3.4) due to solar thermal shading. The cooling loads were found to be much lower and the requirement was lower by up to 3.02kWh per day in comparison to conventional roofs (Kumar & Kaushik, 2005). Results from the mathematical model were also validated against experimental data from a similar rooftop garden in Delhi to establish the accuracy of the model. The results obtained were used to calculate the variation in the canopy air temperature, indoor air temperature and the heat flux through the roof to evaluate the thermal performance of a green roof. Parametric study was carried out to ascertain the effect of green roof components on the thermal performance of the green roof. By varying the Leaf Area Index (LAI) which is the representation of the plan form area coverage of the leaves and height of the vegetation, it was found that a green roof with high LAI was able to maintain a lower average indoor temperature (Kumar & Kaushik, 2005). Larger LAI reduce the canopy air temperature, solar flux and stabilize the indoor temperature.

![Graph showing temperature variations](image)

Figure 3.4: Indoor air temperature variations obtained using building simulation code in the Delhi. (Kumar & Kaushik, 2005)
Unlike many of the earlier predictive studies, the evaluation of the thermal performance of green roof is not localized to the experiment site or dependent on numerical techniques. The predictive model can be incorporated into the building simulation code using Fast Fourier Transform (FFT) techniques in MATLAB to provide results specific to the location. However, it simplifies the effect of evapo-transpiration and soil thermal properties (Castleton, Stovin, et al., 2010). The study is limited in its scope as it discusses the cooling potential of green roofs only. Further investigation may help assess green roof’s behavior in various seasons and assist in creating conditions for achieving the maximum benefit from a green roof installation.

3.5 **Need for further studies**

The potential energy savings of green roofs is widely referred as an important benefit, but it has not been studied in much detail for Delhi. Similar to a traditional roof, the heat gain and loss (which may be referred as the energy balance of the roof) through the green roof is determined by radiation from the sun. In a green roof, the solar radiation is balanced by sensible (convection) and latent (evaporative) heat flux from soil and plant surfaces combined with conduction of heat into the soil substrate.

In the previous Delhi study, green roof modeling was done using a mathematical model. Sailor (2008) identified that existing mathematical models, simplified the energy transfer through green roofs with respect to the effect of evapo-transpiration and soil thermal properties. A new green roof energy balance model created by Sailor modeled the effect of green roof on building (Castleton, Stovin, et al., 2010). The ‘ecoroof’ option in the EnergyPlus software accounts for radiative heat exchange, convective heat transfer, soil
conductance and storage, evapo-transpiration from soil, plants and moisture effects (Castleton, V.Stovin, Beck, & Davison, 2010). The EnergyPlus model can be used to record the thermal impact of green roofs according to the specific location and climate. Since most of the past field studies have been limited to the evaluation of summertime effects of green roofs with a focus on the surface temperature, annual heat gain data for year may be collected for Delhi using the EnergyPlus model. The determination of the most favorable building configuration, orientation and construction materials for a green roof installation and the foliage characteristics that affect its thermal performance will be extremely beneficial for the designers. This data can be collected through parametric studies and this will help evaluate the role of green roofs in thermal load reduction.
CHAPTER 4

DETERMINING THE PARAMETERS

4.1 Aim of the study

The objectives of this thesis are manifold, from evaluation of the success of green roofs in reducing thermal load reduction in buildings; to establishment of the most favorable building configuration, orientation and construction for a green roof installation; to determination of the foliage characteristics that affect the thermal performance of green roofs. To achieve these goals computer model of a green roof was simulated on a building in Delhi.

For the purpose of this study a control building with a 100 sqm floor area and 50 percent opening with a green roof was created. The building activity was defined as office with no occupancy or internal gains and a split system (no air) HVAC system with a 24 hour running cycle. The standard roof construction has a green roof (thickness = 0.200 meter; thermal conductivity = 0.300 W/m-K) with a mud phuska (thickness = 0.075m; thermal conductivity = 0.519 W/m-K) and felt layer (thickness = 0.002m; thermal conductivity = 0.500 W/m-K) underneath, on a concrete reinforced slab (thickness = 0.150m; thermal conductivity = 2.300 W/m-K). All green roof studies were based on this control building and the results are described below.

4.2 Preliminary study: heat gain through building envelope

The thermal loads of a building are governed by its envelope which consists of the walls, windows, floors and roofs. Passive techniques discussed (refer Table 3.1) help reduce the heat exchange through the envelope and reliance on conventional sources of energy. Before incorporating any passive technique into the building design it is important to
analyze the factors that affect the gain through the envelope as majority of the heat gains occur through it.

To ascertain the parameters that affect the performance of the building envelope a preliminary investigation was carried out using the Virtual Environment program. A model 4 storey building with 100 m² floor area and 15 percent wall openings on the North and South sides was created in Delhi. Thereafter the effect of orientation, building configuration and opening percentages on the building envelope studied. It was concluded that certain building configurations and orientations maximize the heat gain and by avoiding them thermal loads for the building may be reduced.

4.2.1 Building Roof

In the study for establishing the effect of orientation on heat gain through the roof, it was observed that the indoor air temperature varied with the building floor. The top most floor of the model building (figure 4.1) with 15% glazing on the North and South face and roof as its top surface recorded the highest indoor temperature.

Figure 4.1: Tested configuration with building openings on North and South facade.
The variation in building orientation from 0° to 90° increased the indoor temperature further. Buildings with south exposure (0° notation in figure 4.2) record low gain as in east and west openings were minimized in the model.

![Figure 4.2: Plot of indoor air temperature of various floors of a four storey building with varying orientations and building configurations (1:1; 1:2; 1:3; 1:4; 2:3).](image)

The same trend of the top floor recording temperatures higher than the rest of the floors is observed on varying building configurations, confirming the role of the building roof as a source of heat gain. Change in building configurations from 1:1 building proportion, to 1:4 results in higher indoor air temperature. Building structures with large roof exposure contribute to high indoor temperatures, solar gain (figure 4.3). Increase in the proportions translates into additional roof, wall surface area exposure to sun leading to greater solar gains. Elongated buildings are source of heat gain and need to be avoided or adequately protected to lower the temperature and solar gains.

![Figure 4.3: A Plot of solar gain through various floors of a four storey building with varying orientations and building configurations.](image)
By varying the different parameters like orientation, building proportions it was observed that the ideal configuration for a building in Delhi was a compact form with the aspect ratio 2:3. In figure 4.3, buildings with 1:1 and 2:3 aspect ratios have lower solar gains compared to other configurations. Buildings with tight footprints have small wall and roof exposure to the exterior which allows adequate exposure to daylight and lower solar gains through the day.

The roof of a structure has the greatest exposure to the sun. An unprotected roof surface receives the heat from the sun and retains it during the day, and releases the stored heat by radiation or convection afterwards (Fry & Drew, 1964). The transfer of the stored heat into the internal spaces increases the temperature and heat gains leading to higher air conditioning loads.

4.2.2 Openings

Design of building fenestration, particularly on the vertical surfaces, determines the thermal performance of a building (Li & Lam, 2000), however, variation in the sun’s path and its course through the day establishes the solar heat gain through it. In the northern hemisphere during winter months, the sun’s path moves toward the South and sun angles become low. Reverse is noted in summers when the sun rises and sets toward the North and solar angles become higher.

The change in sun’s angle requires protection of windows in summers while direct exposure in winters to lower energy consumption. Reduction in external conduction gain and indoor air temperature is observed when the windows are on the North and South façade (represented by 0˚ Orientation in figure 4.4) as low gains for all orientations and building configurations is recorded. Openings on other faces such as the west, (refer to
90° orientation) record high gains and should be avoided or minimized. When external conduction for various building configurations is compared, compact forms (refer to 2:3 in figure 4.4) record lowest gains. As observed blocks with aspect ratios 1:2, 1:3, 1:4 record more gains due to higher wall surface area exposure.

Since the compact ratio of 2:3 records the lowest external conduction the percentage of openings was varied to ascertain the effect of glazing size on the heat gain for the building. An increase in solar gain and external conduction is noted. Results (figure 4.5) indicate buildings with lower percentage of openings are recommended. It can be deduced that openings in a building are a major source of heat gain and need to be carefully designed. By proper shading and use of high efficiency glazing solar gains may be reduced (Johnson, 1991).
4.2.3 Findings

The change in building configuration results in increase of roof and wall area along with the opening proportions and greater gains through the building envelope. Compact building configurations work best for Delhi as they register the lowest external conduction and solar gains through the building envelope.

Along with smaller footprints, east and west exposure should be minimized and resistance to heat flow through the building envelope increased. The roof and the glazing facing the South and West should be adequately protected to reduce the radiant flux entering the building. This may be achieved by shading of the glazing and roof and addition of thermal mass to the building envelope. In the experiments it was established that roofs are a major source of heat gain and by providing additional thermal mass the heat gain through the roof may be reduced. The time lag in heat transfer offered by the thermal mass along with shading of the building may aid a reduction in the air conditioning load.

The green roof is an example of a passive system that uses all of the above techniques to reduce summer gains. Apart from providing thermal mass and shading, it adds insulation and utilizes the evaporative cooling offered by the vegetation to reduce heat flux.

4.3 Green roof study for Delhi

There is a need for comprehensive guideline that can assist designers in Delhi to assess the potential benefit of a green roof with respect to the buildings they design. Using the EnergyPlus green roof module, architects can assess the magnitude of energy savings and evaluate the thermal effect of green roof on the building. EnergyPlus module is based on
a quantitative and physically based building energy simulation which can represent the
effect of green roof construction on the building. The program does not account for the
effects of drainage layer and protection membranes, (Sailor, 2008) but the designer can
specify various aspects of the green roof construction like the growing media depth,
thermal properties, plant canopy density, plant height, stomatal conductance (ability to
transpire moisture) and soil moisture conditions (including irrigation and precipitation).

4.3.1 Green roof model description

The Energyplus engineering reference document states that the energy balance of a green
roof is dominated by radiation from the sun. This solar radiation is balanced by sensible
(convection) and latent (evaporative) heat flux from soil and plant surfaces combined
with conduction of heat into the soil substrate. The green roof model in the EnergyPlus
module accounts for the long wave and short wave radiative exchange within the plant
canopy; plant canopy effects on convective heat transfer; evapotranspiration from the soil
and plants; and heat conduction (and storage) in the soil layer. This energy balance is
illustrated in the diagram (figure 4.6).

\[\begin{align*}
L_f &= \text{latent heat flux of the foliage surface/canopy} \\
H_f &= \text{sensible heat flux of the foliage surface/canopy} \\
I_s &= \text{shortwave radiation} \\
I_{ir} &= \text{incoming long-wave radiation} \\
T_g &= \text{ground surface temperature} \\
z &= \text{height or depth (m)} \\
\alpha_f &= \text{albedo (short wave reflectivity) of the foliage surface/canopy} \\
\alpha_g &= \text{albedo (short wave reflectivity) of ground surface} \\
\varepsilon_f &= \text{emissivity of foliage surface/canopy} \\
\varepsilon_g &= \text{emissivity of the ground surface} \\
\sigma &= \text{the Stefan-Boltzmann constant (5.699*10^{-8} W/m^2 K^4)} \\
\sigma_f &= \text{fractional vegetation coverage}
\end{align*}\]
The energy budget analysis used in the EnergyPlus engine follows the Fast All Season Soil Strength (FASST) model developed by Frankenstein and Koenig for the US Army Corps of Engineers and other plant canopy models. The modeling software uses the energy budget for the foliage layer \( F_f \) and budget for the ground surface \( F_g \) simultaneously to determine the effect of green roofs.

4.3.2 Computational model

To scrutinize model assumptions and the EnergyPlus module the building model in the Delhi study by Kumar et al (2005) was calibrated. A room size of 6 x 5 by 4 with occupancy of 4 people, air change rate of 5 h\(^{-1}\) for a window area of 2m\(^2\) described in the research was created using the EnergyPlus module in the DesignBuilder program. The data collected from the simulation run was plotted against the heat flux values from the Delhi study by Kumar (2005). On comparing the results of normalized temperature data produced a near zero linear relationship. The linear relationship demonstrates a reasonable reliability of the software and the graph in figure 4.7 reflects this relationship.
4.3.3 Green roof simulation

Since the simulation software provides results in heat balance or total cooling load, the variables are used as proxy values for the heat gain and loss through the roof. The *Heat Balance of Roof* represents all of the heat flows into and out of the zone which is given by the sum of heat gains to the zone from external roof to inner surfaces. The surface conduction data for the roof represents the *heat conduction flow* just below the surface of the construction and includes all surface heat transfer mechanisms (convection, long and short – wave radiation). The assumption in heat balance model is that room surfaces (walls, windows, ceilings, and doors) have uniform surface temperatures; uniform long- and short-wave irradiation; diffuse radiating surfaces and one dimensional heat conduction. The sign convention (figure 4.8) used assumes all heat fluxes are positive when energy is absorbed into the layer.

![Figure 4.8: Used sign Conventions](image-url)
Total Cooling load is used as a proxy for determining the cooling potential of green roofs. It is the rate at which total energy (sensible and latent) is removed from the mixed outside and return air stream in order to bring the mixed air stream to the specified temperature and humidity ratio of the supply air stream.

The following series of experiments were designed to evaluate the thermal performance of green roofs while the building materials, aspect ratio, orientation, growing media thickness and foliage characteristics were varied.

4.3.3.1 Variation in construction material

Using parametric studies the varying effect of roof treatment can be better understood. The choice of building material may reduce energy consumption of the building and with major heat gains taking place through the envelope, this impact may be substantial.

a. Roof material

Green roofs offer reduction in annual heat balance of the roof, which is confirmed by the comparison of heat balance of four different roofing systems (figure 4.9), each with a different outer layer and same wall material. The first system is a bare roof with an asphalt-felt coating (Conductivity=1.150 W/m K; Density=2325.00 kg/m³), second is termed white roof and has a white membrane (Conductivity=0.17 W/m K; Density=930 kg/m³), third is a white marble roof (Conductivity = 2.77 W/m K; Density = 2600 kg/m³) followed by the green roof.

When compared with other roofing systems, green roof record the lowest heat flux through the roof. By reducing the thermal peaks during summer months, green roofs regulate the heat gain leading to reduction in indoor temperature fluctuations. However, loss of heat (figure 4.9) to the outdoors in winters may be lowered by adding extra insulation underneath the green roof.
b. Wall materials

Green roofs provide insulation to the building roof, the choice of material for rest of the building envelope components can further enhance or reduce this insulating effect (Abdelrahman & Ahmad, 1991). The selection of clay brick, cement blocks may affect the overall thermal performance. In order to maximize thermal benefit of a green roof the effect of different wall materials on the heat balance of the roof was studied.

Heat balance of the roof with vegetative layer and brick wall (R value = 0.483 m²-K/W) combination was found to be significantly lower than the green roof model with 0.200 meter concrete block (R value = 0.628 m²-K/W) and sandwich panel (R value = 2.045 m²-K/W) walls. R-value indicates insulation’s resistance to heat flow, it may be concluded that the higher the R-value, the greater the insulating effectiveness.

Brick and concrete blocks both have thermal mass and relatively low insulation value and high heat capacity. After neutralizing the heat flux through the roof by using a vegetative roof, it was observed that brick walls are most appropriate because the combination has the lowest heat balance value. Brick walls with high heat capacity help in the quick transfer of heat through the wall compared to other materials (figure 4.10).
4.3.3.2 Variation in aspect ratio

The volume of space inside a building that needs to be heated or cooled and its relationship with the area of the envelope enclosing the volume, affect the thermal performance of the building. This parameter is known as the surface to volume ratio or S/V and is determined by the building form.

In order to establish the optimum building configuration for a green roof installation a study for Delhi with different roof configurations and constant surface to volume ratio were modeled. The total cooling load for the various aspect ratios – 1:1; 2:3; 1:2; 1:3; 1:4 was recorded and compared. The comparison in figure 4.11 for various configurations highlights that 2:3 configuration is advisable due to the lowest annual cooling load.

Figure 4.11: Cooling loads for various building aspect ratios (1:1; 1:1.5; 1:2; 1:3; 1:4) as a proxy for the thermal load reduction capabilities of green roofs.
It was established that for any given building volume, the more compacts the shape, the less wasteful it is in gaining or losing heat.

4.3.3.3 Change in Orientation

Building orientation is a significant design consideration, with regard to solar radiation and wind. As solar radiation affects the energy balance of the green roof, orientation may play a critical role. Building should be oriented to maximize solar gain in predominantly cold regions, while the reverse is advisable for hot regions, (Majumdar, 2001) but that may not be the case for composite climates. Investigating the effect of various building orientations on the heat balance of the green roof, an optimal configuration that maximizes the thermal benefit of green roof may be achieved.

By varying the orientation of the model office which had the green roof, a variation in roof heat balance was observed. On the basis of this change the location of the opening that maximizes this thermal benefit was identified to be the North and South orientation (figure 4.12 and represented by 0° in graph in figure 4.13).

Figure 4.12: The optimal building orientation for Delhi with south glazing. This configuration is represented by 0° in the following graph.
In summers due the high sun angle substantial heat gains may occur through the roof. The variation in the heat balance of the green roof may be attributed to solar gains through western surfaces where afternoon sun causes overheating.

![Figure 4.13 The effect of variation in building orientation (0°, 30°, 60°, 90°) on the annual Heat Balance of the roof.](image)

By orienting the building to the south, solar heat can be captured in the winter and blocked in the summers.

4.3.3.4 Green Roof Characteristics

Green roof assembly varies widely, but there are typically four layers (figure 4.14) a protection layer above the roof to protect it from moisture, a drainage layer for excess moisture to flow out, a growing media (Sailor, 2008) and top layer is the vegetation layer.

![Figure 4.14: Typical Green Roof construction(Sailor, 2008).](image)
Plants regulate the rate of transpiration according to the season and reduce the solar radiation reaching the soil surface (Jim & Tsang, 2010). They achieve this by reflecting a part of the incoming solar radiation and since the role of the green roof canopy is to provide shade the selection of plants is critical. Selection of vegetation with large foliage development or a horizontal leaf distribution ensures low solar radiation transmission (Sailor, 2008). Some of the characteristics that influence the cooling potential of the green roof have been discussed below.

a. *Thickness of growing media or substrate*

The growing medium is the foundation of the green roof assembly as it provides the nutrient base and location for the plants to grow. Typically made up of a combination of sand, aggregate and organic matter it is also known as the substrate. The ideal growing medium allows for the proper drainage, aeration and nutrient for the green roof plants. Properties of the growing media such as its thermal conductivity, specific heat capacity and density play a role in the performance of the green roof. The growing media on a green roof is found above the drainage layer and is determined by water retention capacity, weight, aeration and nutrient retention (Earth Pledge, 2005).

Depending upon the function of the roof, the layer of plants and its characteristics, the growing medium and support system depth may vary. The weight of the substrate is a determinant of the load on the roof (Weiler & Barth, 2009) and varying the depth of the substrate may affect the roof design. A study of the effect of different media depths on the green roof’s performance may help achieve an optimum thickness suitable for Delhi.

For the soil depth study the depth of the substrate was varied based on the industry practices for an extensive, semi extensive and intensive green roof (discussed in detail in
chapter 2). In figure 4.15 lower numbers 0.05m, 0.100 represent the depth of extensive green roof systems, 0.150m and 0.200m the semi intensive while the higher values signify the height of intensive green roofs. Preliminary simulation results indicate that an extensive green roof system is suitable for Delhi.

![Graph showing the effect of varying growing media thickness on the Heat Balance of a green roof.](image)

**Figure 4.15: The effect of varying growing media thickness on the Heat Balance of a green roof.**

It is noted that thicker substrate depth or intensive green roof systems have positive heat balance, implying they retain heat. The greater heat flux through the roof translates into higher demands for cooling (figure 4.16). It is therefore advisable to use short height vegetation like indigenous variety of grasses which do not have deep roots and therefore require less substrate depth for growth.

![Graph showing annual cooling requirement for a building with a green roof when the soil thicknesses are varied.](image)

**Figure 4.16: Annual Cooling requirement for a building with a green roof when the soil thicknesses are varied.**

Since Delhi lags behind in the number of mature green roof installations compared to Europe and United States (Snodgrass & Snodgrass, 2006) the understanding of the best suited growing media and the ideal depth for Delhi may take time.
b. Height of the vegetation

The height of the vegetative layer influences the heat gains and losses through the roof. During the summers taller plants provide shade and the increased evapo-transpiration contributes to the summer cooling. This property of shading is not desirable in the winters as direct gain through the roof is the advantageous for lower heating loads. The relationship between the height of the vegetative layer and the heat balance of the green roof is illustrated below in figure 4.17.

![Figure 4.17: Heat Gain through roof for varying plant heights.](image)

By varying the height of the vegetation from 0.2 meter to 1.0 meter, it was found that a plant height of 1.0 meter increased the heat flux through the green roof (indicated by a positive heat balance in figure 4.17). Negative heat balance may be seen in green roofs that have plant heights in the range of 0.2m – 0.6m indicating lower heat flux through the roof. The reduction in heat flux is beneficial because it is may lower the total annual cooling load requirement for the building. This may not be the case in cooler winter months when green roofs lose heat to the exterior, thereby increasing the heating loads.

c. Leaf Area Index

The LAI along with the leaf angle distribution determines the short and long wave transmittance of the canopy, its effectiveness as a shadowing device (Barrio, 1998). The
leaf area index is the projected leaf area per unit area of soil surface or a representation of the plan form area coverage of the leaves. For example, if roof surface is beneath three leaves, the corresponding LAI is 3 (figure 4.18). The values of LAI are dimensionless but they vary depending upon the type of the plant, but are in the range of 0.5-5.0.

Figure 4.18: LAI assumption for foliage (Kumar & Kaushik, 2005).

To study the influence of foliage distribution on the heat balance of the green roof, the LAI of the green roof was varied from 1 to 5 with 1 indicating the lowest LAI. Figure 4.19 shows an increase in the entering heat flux when the LAI is low. With lower leaf area index (1, 2) the heat balance remains positive for the summer months implying that major heat gains occur through the roof. Higher LAI like 4 or 5 is recommended for the climate as it provides shade to the roof and regulates the heat flux through it.

Figure 4.19: Heat Gain through roof for varying Leaf Area Indices.

The increase in the LAI enhances the ability of the plant to retain air humidity, regulate temperature changes and reduce canopy solar transmittance of summer gains. It may lead to an increase in the winter heating energy consumption (represented by the negative
magnitude of heat balance for LAI = 5) due to the shading effect and thus require additional insulation in the cooler months.

\textit{d. Leaf Reflectivity or Albedo}

Reflectivity or albedo is defined as the reflectivity of the surface to the solar energy incident on the surface. In the EnergyPlus model, leaf reflectivity is defined as the fraction of the incident solar radiation reflected by the individual leaf surface. The solar radiation includes the visible spectrum, infrared and ultraviolet wavelengths (Sailor, 2008). High leaf albedo number (0.4) in figure 4.20 shows that the vegetation on the roof reflects a considerable amount of solar radiation.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{annual_heat_balance.png}
\caption{Annual Heat balance of a green roof for varying leaf albedos.}
\end{figure}

The annual heat balance of the roof is considerably lower for 0.4 (40\%) reflectance when compared to other reflectance values modeled. The reduction in heat flux may also result in lower cooling requirement for the building.

\textit{e. Stomatal Resistance}

The process of water loss through plant respiration also known as transpiration is controlled by the closing and opening of stomata (the intercellular openings between epidermal (guard cells). The resistance to the diffusion of water vapor from these spaces into the atmosphere is defined as the stomatal resistance in the EnergyPlus reference
document (2010). It depends on factors such as light intensity, soil moisture content and vapor pressure difference between inside leaf and the outside atmosphere. Measured in units of $s/m$, the values vary in the range of 50.0-300.0 $s/m$ in the EnergyPlus model. Variation in the stomatal resistance demonstrates that foliage with high values of stomatal resistance result in lower evapotranspiration rates than plants with low resistance. The lower rate of transpiration translates into lower cooling loads (figure 4.21).

![Figure 4.21: The effect of varying stomatal resistances of the vegetation on the annual cooling load.](image)

The stomatal resistance of the leaf is the biophysical parameter that governs the rate of transpiration through leaf stomata for a given environmental condition (Sailor, 2008). Though relevant, but the lack of stomatal resistance values for various species make plant selection based on this parameter difficult.

### 4.4 Discussion

The green roof simulation module described in the EnergyPlus model was tested for Delhi’s climate by exploring the response to numerous parameters like the building materials, orientation, surface to volume ratio and foliage characteristics. It was found that green roofs act as a natural thermal shield and help maintain the temperature of the building. The living ‘green roofs’ offer a natural cooling alternative by providing thermal insulation and evaporative cooling.
The modeling of the green roof and its variation provides an opportunity to explore the energy implication of the green roof design. In Delhi, a compact (2:3 configuration) South facing building with brick walls is best suited to have a green roof installation. In order to maximize the thermal performance of the green roof, the vegetative layer height should be limited to 0.5-0.6 meter, with high Leaf Area Index and reflectivity and low stomatal resistance. In conclusion, the parametric studies present a quantitative estimate of the potential energy savings from a green roof installation. The evaluation can assist life cycle cost analyses of a green roof and help popularize them in the region.

Compared to conventional roofing systems the initial cost of installation, higher maintenance requirements for vegetated roofs may outweigh their benefits. But past studies and the parametric studies discussed in this chapter demonstrate the cooling potential of green roofs and conclude that green roofs reduce heat flux through the roof. An estimate of the energy savings achieved may be useful for facilitating their use in Delhi.
CHAPTER 5

ARCHITECTURAL APPLICATIONS

5.1 Green Roof design process

The green roof design process is no different from the process employed for any other complex landscape architecture installation. The climate, design and building use dictate the various choices for a green roof assembly (Osmundson, 1999). For any green roof project there needs to be an integration of the available expertise and the experience of the designing team. The design of even a small green roof requires an integration of many different components and a coordinated team effort. The team should be aware of the goal of the green roof installation (Luckett, 2009) and have the maximum information before beginning with the design process. Even if an existing building is fitted with a green roof, it is critical to determine the potential benefits to be provided by the green roof, and offset them against the cost of construction, labor and regulatory requirements, codes (Cantor, 2008).

The feasibility evaluation can be carried out through collection of green roof objectives, loading considerations, existing and proposed conditions, building codes. This would enable proper planning and help avoid changes and corrections at a later stage. During the construction phase, sufficient care should be taken to protect the various components of the green roof assembly (Peck, 2008). Since the layers of the green roof are built from the bottom up each layer needs to be tested as it is built and thereafter protected. If the design and program for the green roof calls for a variety of plant materials they need to be procured, installed and maintained (Snodgrass & McIntyre, 2010).
5.2 **Potential for green roofs in office buildings**

Green roofs offer a new alternative for the conceptualization and construction of roof level green spaces. In the past green roof installations have been limited to Europe especially Germany, but are now becoming a part of the green building initiative in other parts of the world. Vegetated roofs are being developed on a variety of structures, in the form of parks, plazas on top of underground parking garages, roof gardens on hotels, residential buildings, bridges, connected podiums and office buildings (Osmundson, 1999) due to the varied benefits they offer. The possible application of green roofs on a wide variety of structures reflects their potential as a system that can be integrated into the urban fabric of Delhi.

Vegetated roofs, especially in office buildings, may serve a variety of functions and range of users. Plants on the green roof make use of the sun’s energy; keep the upper floors cooler by reducing outdoor temperatures. Through photosynthesis plants remove carbon dioxide from the air and lower the pollution levels around the building. The layer of plants protects the underlying membrane from harmful ultraviolet rays and intense heat which may otherwise cause its degradation.

In order to benefit from the thermal properties of green roof a building roof may be partly or fully covered with vegetation. Through green roof design inter-office hierarchy may be enforced. Controlled access may be designated for the private spaces for the office executives, while other green roofs may be left open for the employees and visitors. They can be places of recreation and serve as visual amenities that detract from outdoor roof view of vents, pipes, mechanical equipment. Green roofs with landscaping patterns add to the aesthetics and offer alternative views to the urban roof from neighboring buildings.
5.3 Green roof retrofit

Green roofs offer numerous advantages over conventional roofs which may range from the urban scale to community to individual. Apart from the reduction in storm water runoff, cooling of cities (Stutz, December 2010) tremendous energy savings through the year. The additional mass and insulation provided by the green roof may benefit older buildings with poor existing insulation and that may result in energy savings in summer cooling and winter heating (Castleton, Stovin, et al., 2010). With current building practices requiring higher insulation levels for new buildings, addition of green roofs in older buildings may help bring them up to date with the current.

Older buildings often have more reserve structural capacity compared to newer buildings and therefore can be retrofitted. Stovin et al (2007) found in UK that medium size office buildings with reinforced concrete roof can be retrofitted with a green roof without any structural changes. The comparative study estimated that the capacity of a reinforced concrete slab was much higher than profile steel decking highlighting that the load capacity of the existing roof structure is the primary determinant of the suitability of a green roof installation on an existing buildings (Stovin, Dunnett, & Hallam, 2007). The addition of a green roof affects the size, view and access of the building, hence an inventory of the roof conditions, loading requirements, building codes, occupancy requirements and life cycle status of key components is essential (Castleton, Stovin, et al., 2010) for a successful retrofit project.

Based on the scale of the project, a small retrofit project may or may not require direct supervision from the architect, landscape architect and other consultants. It does require an in-depth investigation into the existing condition and construction documents to
ascertain if the structural members will be able to support the green roof. If strengthening of the structure is required to support the green roof then the additional cost may outweigh the various benefits. To ascertain the suitability of a retrofitting a green roof on an existing building a quantitative evaluation of the energy savings achieved by the use of a green roof needs to be carried out.

5.3.1 Building Selection for the retrofit

Architecture of India like the form of a house is determined by socio-cultural factors of the society, economics, climate, materials, and technology (Rapport, 1969). The buildings in the past respected their environment and relied on the use of local sustainable materials. Various climate responsive strategies like water harvesting, use of dense and compact structures helped counter the intense heat to which the northern region of India is exposed (Sabikhi, 1985).

Twenty years ago a number of architects combined the traditional methods, principles and traditional patterns of building placement (Evenson, 1989). An example of that may be found in architect A.B Lall’s office building for Transport Corporation of India. The three storey modern office building has been designed using traditional Indian design principles and climate responsive solutions (Majumdar, 2001). It is planned to meet high levels of environmental comfort, integration of systems and flexibility for future growth and change. The building is on a rectangular plot in an institutional area near Delhi.

5.3.2 Building description

A prototype of the modern city office, the design of the building is based on the traditional inward looking house (haveli) plan. All materials used in the building are indigenous and attain a new aesthetic in the contemporary form (Majumdar, 2001). The
orientation of the building is determined by the site and entrance contains a planted and shaded forecourt (figure 5.1). The internal spaces orient around the central court which helps shade and facilitate stack ventilation and reduce artificial lighting (Gast, 2007).

Figure 5.1 TCI office, Gurgaon emphasizing the rectilinear form and orientation along a central courtyard.

The skin of the building is made up of a solid insulated wall with windows at lower level and upper levels (Majumdar, 2001). Openings on the wall serve two purposes (figure 5.2), the small windows shaded by the deep reveal, allow insolation in winters and reduce the mid summer sun. Larger windows at the ceiling level are designed for day lighting.

Figure 5.2 Section through the central fountain court of TCI office, Gurgaon (Majumdar, 2001).
The entrance forecourt (figure 5.3) and central fountain court (figure 5.2), to which the building envelope opens have a structural framework that provides support for the retractable shading screens that are stretched according to the season. The body of water in the recirculating water fountain flows over a large surface to maximize evaporation. It acts as heat sink during the cooler months and helps shift the courtyard temperatures towards the wet bulb temperature. Hence the glazing panels around the inner court (figure 5.4) are single glazed since the heat load from the courtyard side are lower (Majumdar, 2001).

After incorporating the day lighting requirements window areas are minimized to 18% of the external wall area (figure 5.5). The larger daylight windows can be adjusted seasonally to control direct insolation and reflect glare free light towards the ceiling for distribution into the office spaces(Majumdar, 2001). The use of tight sealed two layers of
glass provides additional insulation to the daylight windows. They have adjustable Venetian blinds in a double window sandwich. The blinds are adjusted seasonally (thrice a year) by the building maintenance staff to control direct insolation.

Figure 5.5: South – West Elevation of TCI office, Gurgaon (Majumdar, 2001).

Other features like planting scheme along the edges of the site and building materials provide protection from the heat. The heavy mass construction is insulated from the outside by 25 mm thick polyurethane foam protected by a dry red-stone slab cladding. The roof has a 35mm thick insulation with a reflective glazed tile paving cover to minimize the sol - air temperature on the surface (Majumdar, 2001).

5.3.3 Green roof modeling

In the previous chapter computer modeling was used to predict the heating and cooling energy savings of a building with a green roof. Using the same procedure and the ecoroof option in the EnergyPlus model a green roof was modeled as the outer layer of the Transport Corporation of India (TCI) office roof. A comparison between the energy
consumption for the office building with the original roof that consisted of a 35mm thick insulation and reflective tile covering and a vegetated roof was carried out.

The annual heat balance for the two roofs (figure 5.6) show that without a green roof the building roof is a net heat gainer in the summer months (positive heat balance), while reverse is seen with green roofs. The negative heat balance for the green roof during summer confirms that they reduce heat flux through the roof and energy use.

![Figure 5.6: Comparison of heat balance of roof for TCI building with a green roof and without a green roof.](image)

For buildings that have well insulated roofs like the TCI office which has a 0.35m thick insulation and reflective roof tile, the magnitude of thermal benefit ascertained by the reduction in annual chiller electricity load may not be substantial. Improvements of up to one percent reduction in chiller electricity load (refer to figure 5.7) in electricity consumption was observed. Therefore for existing buildings various other factors need to be considered before a green roof may be retrofitted.

![Figure 5.7: Comparison of energy consumption of the TCI building with a green roof and without a green roof](image)
A green roof installation requires additional structural strength on the roof to take the load of the assembly. Apart from the structural requirements, the initial cost of construction and maintenance is high for green roofs and these factors may be prohibitive for their use as a passive strategy to achieve cooling in old buildings. For an existing structure it may be beneficial to explore the addition of high efficiency HVAC system to conserve energy and achieve mechanical cooling together.

5.3.3.1 Benefit of high SEER HVAC system versus a green roof

Energy efficiency ratio (EER) is the ratio of net cooling capacity in kWh to total rate of electric input in watts under designated operating conditions (ASHRAE, 2007). SEER stands for seasonal energy efficiency ratio and it is the ratio of the total cooling output of an air conditioner during its normal annual usage period for cooling energy divided by the total electric energy input during the same period (ASHRAE, 2007). The higher the unit's SEER rating the more energy efficient it is and lower the energy costs.

Three terms are used commonly to describe air conditioning systems- Coefficient of performance (COP), EER, and SEER. EER, SEER are described above and COP is the ratio of the rate of heat removal to the rate of energy input, in consistent units, for a complete refrigerating system or some specific portion of that system under designated operating conditions (ASHRAE, 2007). and is based upon the size of the air conditiong. The EER is related to the COP, as COP is instantaneous measures (of power) while both EER and SEER are averaged over duration of time (to measure the energy). The time duration considered is several hours of constant conditions for EER, and a full year of typical meteorological and indoor conditions for SEER.
A comparison between the simulation run of the TCI building with a low COP HVAC (Heating, Ventilating, and Air Conditioning) system and with a high COP and SEER system show that the annual system energy consumption especially of electricity of the later is much lower (figure 5.8). In Delhi, commonly used air conditioning system is the air cooled with the COP range of 2.78 – 3.8 (ASHRAE, 2007). A higher SEER rating of the air conditioning unit implies energy efficiency and lower energy consumption for the building. Since the building electric load is comprised of the lighting, miscellaneous loads like electronic equipment and chiller load, use of an efficient HVAC system may lead to lower energy costs for the user.

![Figure 5.8: Comparison between the fuel consumption of TCI building. The base case has a HVAC system with COP = 2.7 and a more efficient HVAC system with COP=3.4 or SEER = 13.](image_url)

A green roof was simulated on the TCI building model to ascertain benefit of a green roof installation. Green roof was added to both the scenarios, on the low COP HVAC system building and other with more efficient HVAC system with high COP. Assessment of various set-ups in figure 5.9 highlights that chiller electricity load for the building with high SEER value was lower than base case which had an inefficient HVAC system.
Figure 5.9 Comparison between the chiller electricity load of the TCI building with and without a green roof. The base case has a HVAC system COP = 2.7 while the other has an efficient HVAC system COP=3.4.

It was noted that the addition of a green roof on both the scenarios one even with a proficient HVAC system, lowered the chiller loads but the reduction was not substantial (figure 5.9). However, through the various results a greater reduction in the electric load especially a decrease in the chiller electricity load for the office building was observed when high efficiency HVAC system are used compared to when a green roof was used.

5.3.4 Conclusion

In the research conducted for the retrofit of a green roof on a building, the design cooling requirement for all the floors of the TCI building was evaluated individually. For the lower floors of the TCI building the design cooling remained the same in both cases when the building was modeled with a green roof and without a green roof. It was however observed that the top most floor of the building recorded reduction in cooling loads due to the presence of a green roof (figure 5.10). Overall, a slight improvement of one percent in the chiller electricity load was observed (refer figure 5.7) when the fuel consumption breakdown of the TCI buildings with a green roof and without a green roof was compared.
Figure 5.10: Comparison of the design cooling load for the top most floor of the TCI building with and without a green roof. The base case has a HVAC system COP = 2.7 while other has an HVAC system with COP=3.4.

The major obstacle to the spread of green roofs is the initial cost of installation, which can be anywhere from $15 to $35 per square foot, two to three times the cost of a non-green roof (Stutz, December 2010). The advantage of lower chiller electricity load for the top floor may be lost when energy consumption analysis is carried out and compared to the similar values obtained from a high SEER HVAC system (fig 5.9). The use of a high efficiency HVAC system in an existing building may be more economical and advisable than the installation of a green roof for the purpose conserving energy.

As commercial and institutional buildings are normally repaired or refurbished every 15-20 years (Castleton, Stovin, et al., 2010), a green roof installation may be an opportunity to provide a facelift to the building together with user satisfaction and the thermal benefits. But when these are compared to the life cycle cost, green roofs seem to be a viable passive strategy for new construction only. It is also less expensive to build for a certain capacity from the beginning than to retrofit an already completed structure later.
5.4 **A case for new buildings**

Using experimental research, the effect of green roof (passive cooling strategy for roof) on the building energy system was studied. It was observed that green roofs alone may not be able to reduce the heat flux and cooling load of existing buildings. The cooling effect achieved through the green roof installation, however, may be enhanced by the design of rest of the envelope and incorporation of passive techniques. The external building skin or envelope is the most dominant system amongst all of the subsystems of a building (rest are load bearing structure, mechanical services and spatial services). The envelope performs a number of functions and has substantial contribution to the building energy consumption (Schittich, 2001).

The solar radiation transmitted through roofs and windows (or the envelope) may be direct, diffuse, or reflected from exterior surfaces and it determines the thermal load of a building. Till the late 1960’s and early 1970s internal comfort and the thermal load was largely offset by high performance air conditioning systems (Schittich, 2001). An awareness for energy conservation and provision of a healthy indoor environment lead to a shift from high efficiency systems to the design of the external skin. Primary objective of the building skin which consists of the roof and façade is to regulate the outdoor conditions and ensure comfortable indoor conditions.

The design of the skin must respond to the external environment to lower building air conditioning loads and associated energy costs. To demonstrate the effectiveness of proper building envelope design an office building with the same area, height and requirements as the Transport Corporation building was developed. By recognizing the
climatic conditions of Delhi that range on both sides of the comfort zone, the office design draws upon the external climate to supplement the air conditioning system.

The overall strategy was to minimize energy consumption of the building and reduce the size of mechanical air conditioning through design of the envelope. This was achieved by including various passive strategies that were discussed in chapter 3 into the building design. The building structure has been designed to have a large roof exposure to accommodate a green roof whose thermal benefits have already been established. The development of the office design closely follows the experimental findings of chapter 4. Figure 5.11 describes the various passive strategies that have been incorporated in the design.

Figure 5.11: Passive techniques used
5.4.1 Reduction in solar exposure

The winter sun path is much shorter and lower than the summer path, due to the winter sun rising and setting south of east and west respectively. As a result the east and west facades do not receive significant amount of irradiation in winter, while the same is not true for summer months. The east and west facades become major recipients of summer heat. By analyzing the overheated period chart for Delhi (figure 5.12) for the summer months, it is observed that majority of the solar radiation is incident on the building between 10 am in the morning to 3pm in afternoon, but the heat flux continues until later.

The exposure to solar radiation may be attenuated through the building envelope design. It was discovered in the previous chapters that by controlling solar access heat gain through the roofs and walls were substantially reduced. Through building orientation and shape the objective was to maximize the solar penetration in cold periods, reduced it during the hot dry period and increase ventilation in the hot humid periods.

Figure 5.12: Stereographic diagram representing the Direct Solar Radiation (in W/m²) for New Delhi. (Sun Position -164.6°, 59.4°; HSA – 164.6°; VSA 119.7°) Courtesy WeatherTool
5.4.1.1 Orientation

The amount of solar heat received by the surface of a building was minimized through the manipulation of the orientation and shape of the building plan with respect to the sun movement; height of the building exposed to the sun. In the previous chapter (sec 4.3.3.3) it was established that the heat gain through the building envelope was reduced when the building had a predominant southern exposure. The orientation of the office building has been kept along the east west (figure 5.13), so as to have most of the openings fall on the north and south faces. The windows on the east and west side are minimized and protected by a screen. The orientation exposes the unit to morning sun and cuts the afternoon sun through a screen provided on the south and west side.

Figure 5.13: The chosen orientation for the building

5.4.1.2 Building configuration

The surface to volume ratio (S/V) discussed in chapter 4 expresses the relationship between outside building surface area and the enclosed space that can be used in order to
compare differently shaped buildings containing equal volumes of space. Previously it was found that the building aspect ratio of 2:3 is suitable for climate of Delhi. Through simulations it was found that for any given building volume (figure 5.14) by neutralizing the gains through the building roof by using a green roof, a more compact the shape furthers the thermal benefit. A compact shape receives less solar radiation and is also able to contribute to the building losses.

To demonstrate the above various configurations containing equal volume of space were modeled and the amount of solar radiation incident on its surfaces compared. The buildings blocks are represented by number 1 to 4 in figure 5.14. An analysis revealed that Block 2 recorded the lowest solar radiation on South and North elevations (identifiable by darker hue in first image).

![Figure 5.14: Study of solar radiation incident on various building configurations to determining an ideal form.](image)

Being situated in the composite climate which sees extreme climatic variations, the building adopts an inward looking compact rectangular self shading form with an aspect ratio of 2:3 to limit external exposure. The height above ground has been kept at a minimum to reduce contact with the outside. The entire building has been developed around the courtyard which also behaves like a light well.
5.4.2 Lower level of solar gain

Reduction in the solar gain through the building envelope may be achieved by use of shading devices and design of openings. The roof area of the building has been maximized to avail of the benefit of a green roof installation. The roof is completely covered with vegetation to lower the ambient temperatures and heat balance of the roof.

5.4.2.1 Design of fenestration for ventilation and daylighting

The ideal exposure for Delhi is the South and the East and maximum openings have been provided in this orientation (figure 5.13). Protection has been provided on the overheated south western exposure to eliminate heat gains in summers. The building is developed around a central court which acts as a light well (figure 5.15). The coupling of the spaces with the courtyard allows for good ventilation and the court also behaves like a heat sink.

![Figure 5.15: Section through the light well highlighting the self shading character of the South façade](image)

The thermal performance of the building is the major parameter of design, however adequate distribution of daylight within the internal spaces of the building has been considered. Taking the daylight function into account a light well has been introduced and the window areas minimized. The openings in the external walls are square shaped and at two levels. Small windows at seating height provide for cross ventilation and
views; larger windows at ceiling level designed as light shelves distribute glare free daylight across the office floor. The windows are protected with a venetian blind.

5.4.2.2 Shading devices for fenestration

Reduction in solar gain through the building walls can be achieved by shading devices. An effective means of shading walls and window openings is to extend or project the roof to provide a useful overhang for the lower floors. Since the external wall areas are exposed to low morning and afternoon sun the heat transfer through the wall is controlled through shades and screens. The windows of the office building are provided sun shading by the overhang of the upper floors (figure 5.15). The overhangs obstruct the high sun angle and reduce the direct solar gain.

The south and west sides of the building are protected by additional screens (figure 5.16) that project beyond the overhang of the upper floors. This prevents the summer heat from entering, while allowing winter radiation to penetrate. A protective screen made up of horizontal and vertical members shields the openings from the oblique South East and North West sun angles, and at the same time allows cross ventilation.

![Figure 5.16: Screen protecting the South West facade](image)

5.4.2.3 Use of green roofs for shading roofs

The essential role of the canopy in green roof is to shade the structure below. It has been established in the previous sections that building roofs are a source of heat gain for the
building and therefore, need to be protected from direct solar radiation. Green roofs not only provide shade (through vegetation) to the roof, but also add thermal mass. The plants on the green roofs shade the roof membrane and reduce the ambient temperature. The selection of plants with large foliage development or horizontal leaf distribution (figure 5.17) on a green roof ensures a low solar heat transmission into the building as the foliage provides an insulation cover of still air over the roof which impedes solar flux. The evapo-transpiration of the plants utilizes the solar heat and helps cool the roof.

![Figure 5.17](image)

**Figure 5.17**: A section through the green roof showing how the vegetation shades the building roof. Image courtesy Weiler (2009) and changes made to it by the author.

The roof area in the building design has been maximized to capitalize on the thermal benefit green roofs offer. The building roof is completely covered with a green roof and in return it shades the roof membrane and slab from direct solar gain. A combination of tall and short height plants help in increasing the LAI. It section 4.3.3.4 it was concluded that high LAI is recommended as it provides shade to the roof.

5.4.3 Resistance to heat transfer through the envelope

The amount of heat conducted into the building through its skin is dependent on the thermal resistance of the material and its heat storage capacity (Majumdar, 2001). The
absorption of solar radiation by the outer surfaces and its transmittance through the roof and walls to the internal surfaces causes discomfort for the users.

5.4.3.1 Choice of insulating materials

The office building is designed for predominantly daytime use and the material selection is governed by that. The addition of insulation will be of value when the average daily temperatures outside the building envelope fall or rise above the comfort zone (ASHRAE, 2007; Watson & Labs, 1983). In the study conducted for Delhi (chapter 4) it was observed that brick walls with a green roof assembly furthered indoor comfort.

For the office building exposed brick walls that are 345 mm thick have been used on the external surfaces. They have a time lag of about 8 hours, and an overall heat transfer coefficient (U-value) of 1.9 W.m²˚C (Majumdar, 2001). Additional insulation is provided by the double glazing low e windows that have been provided for the daylighting.

5.4.3.2 Use of thermal mass

It is necessary to insulate the roof as it receives majority of the solar radiation in summer owing to the high sun angles of Delhi. A green roof has been used to provide additional thermal mass to the roof which delays the heat flux into the building. In the previous section (4.3.3.1) it was observed that green roofs have the lowest heat balance establishing their success in mitigating solar gain through the roof. The additional mass on the roof helps regulate the diurnal swings in temperature during day and night.

5.4.4 Increase heat loss through envelope using green roofs

5.4.4.1 Use of Vegetation to achieve a cooling effect

Proper selection and positioning of plants can improve the microclimate of a site. Green roofs use vegetation to reduce the cooling load on buildings. The role of the canopy in a
green roof is to provide shade to the structure below and lower solar gains through the building roof. Best plants to use are native varieties that have adapted to the local climate and soil as they require less water, fertilizer and chemicals for its growth. The thermal mass of the soil damps out the temperature fluctuations in both summers and winters as a result the structure is subjected to relatively small heating and cooling loads. Selection of light soil may also help reduce thermal conductivity and lower the dead weight of the roof.

5.5 Building Views

Figure 5.18: South West Building View showing the screens
5.6 Cooling load benefit

A comparison between the cooling loads for the TCI building (building that was modeled for the green roof retrofit) the new office design was carried out to ascertain the reduction in cooling achieved. By incorporating passive techniques into the building design a
reduction of up to 36 percent in the design cooling load was noted. In figure 5.23 the base case represents the TCI building without the green roof while the New Design + shade represents the building design developed using passive design techniques. The reduction in cooling load means a smaller HVAC system would be required for the new building for the same building area as the TCI office building. This can lead to financial incentive for the owner as there would be substantial savings in the cost of cooling equipment and energy costs.

![Figure 5.23: Comparison of Design cooling loads for building with same floor area.](image)

The cooling load for the buildings with green roofs (refer base case+ green roof and High SEER +green roof in graph 5.2) is lower than the counterpart buildings (Base case and High SEER) which had no vegetation on the roof. This reduction of approximately 10 percent establishes that green roofs are successful in lowering the heat flux through the roof and may be used a passive cooling strategy for Delhi in combination with other techniques in the future.
The comparative study confirms that in order to lower the thermal loads for a building, passive design strategies need to be incorporated into the building design. For internal load dominated office buildings, a reduction of 30 percent may be substantial as it can considerably lower the energy consumption for the building and its associated costs.

5.7 Conclusion

The design strategy was not to control the thermal performance of the indoor spaces – rather to integrate features that would shift its overall performance passively toward comfort. Air conditioning will always be among the greatest expenses of a building during its lifetime. It is largely dependent on the heat transfer through the building fabric and the most effective strategy for reducing the thermal load and the subsequent energy consumption, is through the design of the building envelope. That may be achieved through the addition of thermal mass, insulation, shading to name a few. The current exploration of sustainable building designs in modern Indian architecture affirms that the future is likely to be dependent on high efficiency systems and green design.
CHAPTER 6

CONCLUSIONS

Over the last couple of years many new green roof installations have been built around the world but little research into the performance of green roof systems in composite climate has been conducted. The literature that exists consists primarily of studies carried out in the extreme hot and cold climates. Green roofs are a substitute for natural landscaped areas at ground level which are scarce in urban centers like Delhi. The Landscape roofs offer many benefits, starting with the additional building insulation, lower requirements for air conditioning and energy, mitigate the heat island effect, reduce the total area of impervious dark surfaces in city to name a few. With emergence of Delhi as a major urban center of India, green roofs can become a part of the local building practices to improve the urban way of life.

6.1 Comparison of benefits with conventional roofs

The various experiments carried out through the course of this thesis have confirmed that green roof installations have wide ranging advantages over traditional roofs. The benefits of green roofs may be categorized under a range of scales. Some of the benefits are appreciable only when a large number of green roofs are implemented at the larger neighborhood or urban scale, while others may be availed at the individual building level. Even when the advantages at the building level are not that substantial, green roofs add value to the structure. Vegetated roofs provide an outdoor healthy space for the user, add aesthetic value to the building, benefits that are not tangible. The following table (6-1) compares the positive aspects of a green roof installation with a conventional roof.
<table>
<thead>
<tr>
<th>Benefit</th>
<th>Green Roof</th>
<th>Conventional Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storm water volume retention</td>
<td>10-35% during wet season, 65-100% during dry season</td>
<td>None</td>
</tr>
<tr>
<td>Temperature mitigation</td>
<td>In hot season</td>
<td>Achieved with insulation</td>
</tr>
<tr>
<td>Improved water quality</td>
<td>Retains atmospheric deposition and retards roof material degradation. Reduced volume reduce pollutant loadings</td>
<td>None</td>
</tr>
<tr>
<td>Urban Heat Island Mitigation</td>
<td>Prevents temperature increases</td>
<td>With Light colored roof ,e.g. white roofs</td>
</tr>
<tr>
<td>Air Quality</td>
<td>Filters air and increases evapotranspiration</td>
<td>None</td>
</tr>
<tr>
<td>Energy Conservation</td>
<td>Insulate building roof</td>
<td>Through Addition of insulation, light colored roof and shading reduction in energy consumption may be achieved.</td>
</tr>
<tr>
<td>Vegetation</td>
<td>Allows seasonal evapotranspiration; photosynthesis,</td>
<td>None</td>
</tr>
<tr>
<td>Green Space</td>
<td>Replaces green spaces lost to due to the building footprint</td>
<td>None</td>
</tr>
<tr>
<td>Habitat</td>
<td>For bird and insects</td>
<td>None</td>
</tr>
<tr>
<td>Other advantages</td>
<td>Buffers noise, alternative aesthetic, offers passive recreation</td>
<td>None</td>
</tr>
<tr>
<td>Total Costs</td>
<td>Highly variable from $53.8-129.12 m² new construction and $75.32-215.20m² retrofits</td>
<td>Highly variable from $21.52-$107.6 per m² new construction and $43.04m²-$161.40 per m² retrofits</td>
</tr>
<tr>
<td>Cost offsets</td>
<td>Reduced storm water facilities, energy savings, higher rental values, increased property values, reduced need for insulation materials, reduced waste to landfill</td>
<td>None</td>
</tr>
<tr>
<td>durability</td>
<td>Waterproof membrane protected from solar and temperature exposure lasts more than 36 years; membrane protected from maintenance damages</td>
<td>With Little protection and exposure to elements, roofs may last less than 20 years.</td>
</tr>
</tbody>
</table>

The advantages of a green roof are often outweighed by the financial cost incurred in their installation. They generate tangible benefits in the form of financial returns from energy savings and smaller HVAC system, roof life longevity and the less quantifiable social and environmental benefits such as storm water runoff reduction, UHI mitigation,
habitat for urban biodiversity to list a few. A variety of design elements and green roof components contribute towards the various advantages discussed above.

6.2 Summary of findings

One of the great advantages of green roofs is the reduction of summer cooling load. Although the wet soil is a poor insulator, the transpiration from the plants and evaporation from the soil cool the plants, soil and the air. In a three story building the cooling load may be reduced by as much as 30 percent. With sustainable building design practices being part of the modern day architecture of India it is evident that the future is likely to involve green architecture and energy efficient design, and green roof installations can contribute towards this goal.

6.2.1 Building design

Using parametric studies optimum design practices that enhance the thermal benefit of green roofs in composite climate were identified. It was found that compact buildings that have low surface to volume ratio like 1:1 and 2:3 (1:1.5) building configuration and are along the north south axis perform the best. The lower surface to volume ratio ensures minimum heat gain through the building envelope and low height buildings further this reduction as the surface area exposed to the sun is minimized.

The impact of green roofs is highest in buildings that are up to four storeys high. In these buildings the roof is still the major source of direct gain and installation of a green roof provides shade, thermal mass to the roof and regulates the ambient temperatures. In buildings taller than four floors, due to the large wall surface exposure, the envelope becomes a substantial contributor to the building thermal gains. The gain through the
building envelope often supersedes the thermal benefit obtained by installing a green roof, thereby limiting the thermal role of green roofs in taller buildings.

After neutralizing the heat gains through the building roof using a green roof, the next source of solar flux which is the building envelope needs to be addressed. Use of high thermal mass or insulation providing materials and shading of the external surfaces can lower the thermal gains of the building. Proper fenestration design with openings on the North and South facing walls ensure winter heating and protection in the summer months for reducing the heat gains. Self shading courtyards can further aide ventilation and indoor daylighting and become a heat sink for the building.

6.2.2 Green roof components

If a new or an old building is being planned with a green roof, the designer should be aware of the issues concerning the structural design, drainage and logistics and the native plant species. Various considerations for the green roof components such as the vegetation layer; growing media and the structural support layer are discussed below.

6.2.2.1 Vegetation

Plants are immensely useful in cooling of buildings and have been shown to enhance human health and performance. Best plants to use are native varieties that have adapted to the local climate and soil as those trees require less water, fertilizer and chemicals for its growth. Plant species that have a dense summer canopy (high LAI) and an almost branchless open winter canopy are beneficial as they increase the plant transpiration rate and help retain the humidity in air. The multiple layers of leaves are ventilated by the transpiration (evaporation) of water from the leaves in summers. Transpiration not only cools the plants but also the air in contact with the vegetation. The cooling load on a
building with vegetation was always found to be smaller as the plants help buffer against the outdoor conditions compared to building surrounded by asphalt or concrete.

6.2.2.2 Substrate
A variety of substrate depths were modeled using the EnergyPlus module in the green roof on the model office building. It was observed that extensive green roofs are beneficial for Delhi as they have the lowest heat balance for the roof. For the vegetation to flourish plants need the right amount of water, nutrient and drainage. The drainage and retention layer complement the work of the soil as they regulate the moisture content by getting rid of the excess water.

6.2.2.3 Structural support
The decision to incorporate a green roof into an existing or a new building requires an evaluation of a number of factors. Not every structure may be capable of supporting the extra load generated by the green roof. Therefore, an analysis of the structural capability of the roof is required before any retrofit project is undertaken. The configuration of the roof plays an important part in the design and it should be flat to support the green roof. A new green roof design needs to take into consideration the higher dead load, deep soil pockets and requirements of the vegetation.

6.3 Impact of the study
Data collected from various experiments conducted for evaluating the thermal performance of a green roof may help designers with quantifying the benefits. Designers will be able to incorporate green roofs with envelope or skin load dominated buildings. The contribution of green roofs would be maximized, as the buildings that rely on
mechanical cooling significantly will have reduced thermal loads through the roof, and smaller sized HVAC systems.

If used with other passive strategies green roofs can contribute towards energy efficiency in the building. Apart from reducing the cooling load for the building, green roofs provide other intangible benefits like storm water management, outdoor green space, and aesthetic value addition to the building roof. Some of these advantages may outweigh the initial cost of construction.

The designer now has access to the various parameters like the building orientation, construction materials, building configuration, foliage characteristics which affect the performance of the green roof. The architect can therefore, design a new or a retrofit green roof and capitalize on the thermal benefit.

6.4 Limitations

This study addresses the thermal performance of green roofs in composite climate only. The geographic location for the composite climate was set as the metropolitan region of Delhi and all the simulations were carried out for that location. The number of parameters by which thermal performance of green roofs are evaluated are limited. The categories used for the evaluation are orientation, building configuration, building materials and plant characteristics. The heat balance of the roof and the resultant cooling load is used as a proxy for determining the effectiveness of the green roof system. As the study relies on computer software for the modeling of green roofs only an energy analysis is provided, other benefits like food production, storm water mitigation, habitat for plants, animals, opportunity for carbon sequestration are mentioned, but not covered in the study.
6.5 **Future work**

In this thesis various factors that affect the green roof’s thermal performance were studied. A detailed study of the substrate layer would help maximize this benefit as the soil layer plays an important role in the cooling of the roof. The substrate layer supports the vegetation and the evaporation of water from this layer helps achieve ambient cooling.

An investigation of the effect of irrigation on the green roof during summer months may be beneficial as it would help ascertain how the performance of the green roof varies with wet soil. The plant species that are suitable for the region may also be determined by this analysis. It may also help establish which kind of substrate and what depth would be resistant to the harsh conditions.

In addition to the parameters used in this thesis, a battery of tests and simulations to prove the viability of a green roof in a particular situation, which incorporate the above aspects, may be beneficial. The list of experiments would assist professionals and firms to optimize their information and make best decision.
Appendix A

Green roofs may become an important contributor to the urban green movement. Native plants species and grassland plants are particularly adaptable to this manmade habitat. A native green roof will provide habitat for wildlife, especially insect pollinators adding to the biodiversity value of these efforts. Based on the list of plants for a green roof created by the National Park Service, New York (GNPC, 2011) and the guide to species of trees found in Delhi (Krishen, 2006) a list of vegetation for green roof installation in Delhi has been created.

List of vegetation suitable for a green roof in Delhi

1. **Grasses:** Grasses are the most abundant, widely spread, and useful of all flowering plants. They provide the bulk of green herbage, dried fodder and a variety of valuable byproducts such as fibers, paper, sugar, aromatic oils, and adhesives (Hubbard, 1954). Technically known as graminoids, are herbaceous plants with narrow leaves growing from the base. They have highly developed root-systems, close vigorous growth, and ability to persist under adverse conditions. The special type of leaves enables the plants to withstand close and frequent cutting.

*Dry grasses:* Carex pensylvanica– Pennsylvania sedge; Cyperus echinatus– Globe flatsedge; Danthonia compressa– Northern oatgrass; Danthonia spicata– Junegrass; Deschampsia flexuosa– Common hairgrass; Eragrostis spectabilis– Purple lovegrass; Schizachyrium scoparium– Little bluestem; Sorghastrum nutans– Indian grass.

*Dry to Moist grasses:* Andropogon virginicus– Broom sedge; Juncus tenuis– Slender yard rush; Panicum clandestinum– Deertongue; Panicum virgatum– Switchgrass; Tridens flavus– Tall reedtop
**Moist to Wet grasses:** Carex lurida– Shallow sedge; Carex scoparia– Broom sedge; Carex vulpinoidea– Fox sedge; Juncus effusus– Smooth rush; Scirpus atrovirens– Bulrush; Scirpus cyperinus– Woolgrass; Scirpus pungens– Chairmaker’s rush

2. **Herbs:** Herbs are defined as any herbaceous or woody plants that may be used for flavor, fragrance, medicine, dyes, soaps etc (DeBaggio, 2009). Herbs grow best in soils with excellent drainage properties. They require up to six hours of bright sun, and moderate temperatures and should be watered thoroughly once a week by soaking the soil to a depth of 8 inches ensuring the roots receive adequate moisture (Bremness, 1994).

**Dry Herbs:** Baptisia tinctoria– Wild indigo; Chrysopsis mariana– Shaggy golden aster; Eupatorium hyssopifolium– Hyssopleaf thoroughwort; Euthamia tenuifolium– Coastal plain flat-topped goldenrod; Monarda fistulosa– Wild bergamot; Oenothera biennis– Common evening primrose; Opuntia humifusa– Eastern prickly pear; Pycnanthemum tenuifolium– Narrowleaf mountainmint; Solidago caesia– Bluestem goldenrod; Solidago canadensis– Common goldenrod; Solidago juncea– Early goldenrod; Solidago nemoralis– Gray goldenrod; Solidago rigida– Stiffleaf goldenrod; Symphyotrichum cordifolium– Bluewood aster; Symphyotrichum ericoides– White wreath aster; Symphyotrichum laeve– Smooth blue aster

**Dry to Moist Herbs:** Eupatorium serotinum– Late flowering thoroughwort; Euthamia graminifolia– Flat top goldenrod ; Geum canadensis– White avens; Penstemon digitalis– Tall white beard tongue; Rudbeckia hirta– Black–eyed susan; Uvularia sessilifolia– Bellwort; Verbena urticifolia– White vervain

**Moist to Wet Herbs:** Chamaecrista fasciculata– Partridge pea; Chelone glabra– Turtlehead; Eupatorium fistulosum– Trumpetweed; Eupatorium maculatum– Spotted joe-
pye-weed; Helenium autunnale– Sneezeweed; Lobelia cardinals– Cardinal flower; Lobelia siphilitica– Indian tobacco; Ludwigia alternifolia– False loosestrife; Pycnanthemum virginianum– Mountainmint; Solidago rugosa– Tall Hairy goldenrod; Symphyotrichum novae–angliae– New England aster; Thalictrum pubescens– Late meadow rue; Verbena hastate– Blue vervain.
References


