Investigating and Promoting Extensively Natured, Green Urban Rooftops in Puerto Rico

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Submitted by
Jared Deck
Andrew Frank
Brian Miley
Travis Weber

Submitted to
Project Advisors
Scott Jiusto
Lauren Mathews
Project Sponsor
Ángel David Cruz
WPI Director Puerto Rico Project Center
Susan Vernon-Gerstenfeld
Local Coordinator
Beatriz Arsuaga

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Greenbuildings-d05@wpi.edu

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Abstract

This report, prepared for the University of Puerto Rico at Rio Piedras, investigated the feasibility and desirability of utilizing vegetated (green) roofs in the tropical climate of San Juan, Puerto Rico. Feasibility was assessed through experiments on the performance of various plants and soils and development of a temperature sensor network to collect data for a heat transfer model. Desirability was assessed through interviews with employees in targeted industries. Green roofs were found to yield substantial benefits at both the economic and environmental level.

Acknowledgements

WPI Director Puerto Rico Project Center
Susan Vernon-Gerstenfeld

Local Coordinator
Beatriz Arsuaga

Project Advisors
Scott Jiusto
Lauren Mathews

Project Liaisons
Dr. Ángel David Cruz, Geography Department, University of Puerto Rico

Executive Summary

The goal of this project was to investigate the feasibility of utilizing green roofs in San Juan, Puerto Rico. Puerto Rico, a U.S. Commonwealth, has experienced significant economic and industrial growth in the past 60 years as a result of ambitious leaders and favorable relations with the U.S. Unfortunately, this economic and industrial development has led to a strain on Puerto Rico's resources. There is significant urban development and alteration of the natural habitat. Puerto Rico also lacks its own energy sources so it must rely on imports for nearly all of its energy needs.

Green roofs present a unique opportunity to both restore natural green spaces that have been taken by urban development and to reduce energy consumption in San Juan. Studies in Europe and the U.S. have documented significant energy savings, runoff reduction, air pollution reduction, and protection of the rooftop from the elements. It is also believed that green roofs work to mitigate the heating of the local atmosphere that occurs around major cities.

These benefits can be realized using various green roof systems. One system, the extensive green roof, utilizes a minimal substrate layer and hardy, low-maintenance vegetation creating a minimal structural load and ease of operation for building owners. Another system, the intensive green roof, utilizes deeper soil that can support a larger variety of vegetation including trees and shrubs. This type of roof provides all the benefits of an extensive roof and also provides an area that can be used and appreciated by people. However, it is more expensive than the extensive system and requires additional structural support. Both systems provide significant protection to the building's roof, with green roofs on record in excellent condition after more than 40 years.

Despite all the benefits of green roofs, they are scarcely used in Puerto Rico. Some causes of this are a lack of knowledge about green roofs in general, a lack of confidence in their benefits, and an unwillingness to pay the high initial cost of green roofs compared to traditional roofs. In response to this situation this project was designed to investigate the different factors controlling the implementation of green roof technology in Puerto Rico. These objectives are listed below with a short description of their purpose.

- Analyze and recondition the green roof: Measurements taken on a healthy green roof fed our life-cycle cost analysis model.
- Initiate a long term study of alternative plant and substrate options: For green roofs to succeed in San Juan, a hardy, low-maintenance, low-cost combination is essential.
- Design and implement a temperature sensor network to provide data to be used in life-cycle analysis and in future exploration.
- Create life-cycle cost comparison for green and traditional roofs: This model can help convince people of the benefits of green roofs and persuade them to overlook the high initial cost.
- Research the knowledge of and attitudes towards green roofs through interviews of targeted individuals: This will help to identify further barriers or opportunities for the development of green roofs.
- Recommend further steps for the development of a green roof industry: This will allow others to continue to work towards implementation of green roofs in San Juan.

The first objective of this project was to recondition the existing roof at the University of Puerto Rico at Rio Piedras. This roof was found to be in poor condition. Through watering, seeding, and fertilizing we were able to restore it to a condition which would portray the important characteristics of a healthy green roof.

The second objective of our project was to compile a list of plants and soils that could be used on green roofs in San Juan. It was essential to determine which plants and soils could sustain the alternating periods of heavy rainfall and extended drought that are common to Puerto Rico's climate. Other desirable characteristics for green roof plants include a low mature height and full ground cover. A plant list was compiled through research of green roof companies and plant databases, and edited through contact with botanists and professors at UPR. The growing medium is another key component of green roofs. Desirable characteristics of substrate material include the provision of good aeration for plant roots, sufficient porosity to retain nutrients and water, and durability so that the soil does not wash away. Soil experts were consulted in order to determine a substrate that fit these needs. A test was designed to compare volcanic rock, which is commonly used on green roofs, and limestone, which is locally available, as well as test different plants in a green roof situation. The various plants and substrates were set up in a long term experimental plot that could be monitored after the term of this project. Eight species were transplanted into the experimental plot along with the two substrates. Each plant species was planted side by side in each substrate to compare growth over long term observations. These observations were set up to be easily passed along to other individuals after we leave this project. We were not able to tell which plants would survive in the long run on a green roof, but the plants and materials selected have a reasonable chance of success given their characteristics and provided a basis for pricing those types of materials for the life-cycle cost analysis.

The third objective of the project was to create and implement a temperature sensor network. After researching temperature sensing the components of the network were selected and purchased. The components of the system were connected to a computer which runs a piece of software which we designed to manipulate the raw data and output it as temperature values. The temperature network served two purposes in this project. First it was setup to simultaneously record the temperatures on the green and a traditional roof. The data from this exploration was used in the heat conduction model which will be mentioned later. Second the network was arranged on the green roof to constantly monitor its temperature at different points. This data can be used in future explorations of green roof technology.

The fourth objective involved developing a life-cycle cost model for a traditional and a green roof. This model encompassed installation costs, maintenance and repair costs, and the cost of energy transferred through both roofing systems. The physical costs of both roofs were determined through communication with suppliers and builders of the respective roofing systems and related components. Green roofs installed were found to cost around \$20.00 per square foot whereas traditional roofs cost only \$4.00 - \$5.00 per square foot. Energy costs were determined through analysis of the heat transfer through the roof. Results of the heat transfer analysis varied substantially with changing weather, but it was found that the annual cost of energy used by a green roof was approximately \$0.20 per square foot whereas that for traditional roofs was \$0.54 per square foot. When all the costs for both roofs were determined, they were plugged into a life cycle cost analysis model. Life-cycle costs over the 40 year period for green and traditional roofs were found to be \$25.21 and

$27.78, respectively. This verified that green roofs are viable from a cost perspective, even without the type of government assistance that commonly supports green roof construction in places like the United Kingdom and Germany. The energy savings on the individual level were then scaled to energy savings at the macro level in order to develop a conceptualization of the benefits of green roofs to society.

The purpose of the final portion of our project served the dual purpose of spreading knowledge of the function and advantages of green roofs while gaining information about the public's knowledge and understanding of green roofs. We targeted three general groups of people to talk to, including those that may eventually be involved in the construction of green roofs, those that may eventually become customers to a green roof industry, and those groups who may have an interest in encouraging the use of green roofs. We set up interviews and meetings with individuals from each of the groups and presented information geared to the specific interests of their status in one of those three groups. Included in this information were the results from the feasibility study. From these talks, we learned valuable information about the perception of green roofs, reservations people may have about the use of green roofs, and potential support for green roofs.

We recommend that those who continue this project maintain the experimental plots to examine the long-term performance of the plant and soil combinations. A long term protocol has been set up to aid in this pursuit. We also recommend that communication lines with several of the important contacts we have made in the various sectors be maintained, and the findings of our life-cycle cost analysis be dispersed to show that a preliminary study has verified the favorable performance of green roofs in Puerto Rico. Building on the findings of this project has the potential to lead to more in-depth research and possibly the beginning of a new, environmentally responsible industry to help the people of Puerto Rico move towards an environmentally sustainable society.

1 Introduction

As society has become more industrialized, its negative impact on the environment has significantly increased. Industrialization replaces natural terrain and vegetation with manmade structures, in turn affecting both the local environment and, as many studies have shown, global climate patterns (Hartmann et al, 2000). Alteration of the environment is inevitable when one considers the nature of modern civilization- the great need for transportation and the dependence upon fossil fuels in economies across the globe. However, the vast majority of industrialized societies are rife with irresponsible and inefficient energy practices. Several examples can immediately be identified: the use of excessively large personal vehicles when a smaller and more efficient model would suffice, factories that dispose of harmful wastes inappropriately, liberal and inefficient uses of energy sources, inefficient design of urban spaces and infrastructure systems, irresponsible destruction and alteration of the natural landscape, noise and temperature pollution, and excessive waste. Urban areas are at the same time the greatest cause and victim of the effects mentioned above. This does not mean that they are inherently bad for society or the environment. On the contrary, a high population density means less urban sprawl and encroachment on the natural environment. However, it does mean that urban areas can do a better job of mitigating their effects on the environment.

Puerto Rico is an island about two-thirds the size of Connecticut (Bureau of the Census, 2003) which has experienced rapid urbanization in the past 60 years. From 1940 to the present Puerto Rico's population has more than doubled, growing from about 1.9 million to 3.9 million in that time (Osterkamp, 2001). Today, 79% of the population is urban as opposed to 30% in 1940. Due to the steep slopes of the mountainous interior region, 85% of the island's 3.9 million people live in urban areas within 5 miles of the coast (Osterkamp, 2001). Puerto Rico's government was able to transform its economy from one dependant on agriculture to an industrialized state with several modernization programs from the 1940's to the present day. This rapid urbanization was accompanied by lax regulations and lagging infrastructure to support the development, exacerbating the negative environmental impacts that a more sustainable type of growth may have produced (Hunter and Arbona, 1995). The result is a modern San Juan with a high demand for imported petroleum (Puerto Rico Fact Sheet, 2004) and a city that adversely alters its local climate, displaces indigenous species, and pollutes the water and the air.

An ideal solution to the environmental problems and energy shortage in Puerto Rico would be to encourage urban businesses to pursue a path of development that Puerto Rico's damaged environment could support. One way to accomplish this is through the use of vegetated or "green" roofs. However, this approach has not been utilized; instead Puerto Rico's government has pursued other means of reconciling its industrialized society with the environment.

For example, in order to force treatment plants to stop placing untreated waste into Puerto Rico's streams, the EPA has exacted fines on many sewage treatment plants found guilty of violations. In a three year period from 1989 to 1991, these fines totaled $3,000,000 (Hunter and Arbona, 1995). Unfortunately, all the fines in the world will not solve the problem when the amount of incoming waste simply exceeds aggregate capacity.

Puerto Rico has also looked into alternative energy sources as a way to alleviate high energy costs. Coal and gas burning facilities are set in place and are increasing the overall energy production, and ideas of considering a waste-to-energy plant have been brought forth

(Miranda and Hale, 2005).

Although reactive measures such as regulations and alternative energy sources certainly would help San Juan's energy and environmental problems, proactive measures could prove to have a more significant impact. Vegetated rooftops present a unique opportunity to both cut energy costs and decrease the environmental threats of climate alteration and water pollution.

The technology to construct vegetated roofs has existed in one form or another for decades. The green roof has been proven as an economical alternative to traditional roofs when life-cycle costs are considered, and its benefits to the environment are documented extensively (e.g. American Forests, 1995, EPA, 2000, Osmundson, 1999, Solomon, 2003). However, construction of such roofs remains uncommon in most areas of the world. In fact, the only vegetated roof in San Juan is one used for testing by the University of Puerto Rico. The scarcity of green roofs is due in large part to the public's lack of knowledge about such roofs and the high initial installation cost.

This project examined the environmental issues present in San Juan and the surrounding area and demonstrated how traditional roofing systems contribute to these problems. It assessed the extent to which a green roof will not only help to mitigate the various forms of environmental pollution created by the urban environment but also contribute additional societal benefits specific to Puerto Rico. We examined the local business environment as well as various ways in which green roof technology has been implemented in other regions in order to recommend a strategy for aiding the construction of green roofs and the beginning of an industry that will help to steer San Juan onto a path of sustainable development.

2 Background

2.1 Introduction

The economy of Puerto Rico was once primarily agricultural. Sugarcane dominated the economy, accounting for 70% of the island's exports. However, the sugar cane industry suffered a sharp decline, peaking in 1952 and teetering almost to disappearance by 1992. During this time, after World War II, the Puerto Rican Government implemented a program known as Operation Bootstrap, designed to revitalize and modernize industry and the economy in Puerto Rico. This program attempted to mobilize an unemployed population and create an island of industry (Santana, 1996). It provided most of the island's jobs in the second half of the twentieth century and worked brilliantly in rapidly transforming the island into a modern, industrialized, and largely urbanized society. However, in the end Operation Bootstrap did little to solve the island's unemployment, but widened the inequality gap of the middle- upper class and the poor majority, as well as the gap between urban areas such as San Juan and the rest of the island. It also instilled a legacy of industrial and urban development with little consideration for the environment.

The following sections investigate the environmental and economic problems of San Juan, the nature of green roof construction, and ways in which San Juan may benefit from green roof construction. Section 2.2 examines the contributions of traditional roof structures to economic and environmental difficulties. The evolution of the green rooftop industry from its fledgling stage in 1950's Europe to worldwide usage today is shown in Section 2.3. Section 2.4 looks at the various types of construction used in modern green roofs and presents a life-cycle cost model that details the feasibility of constructing a relatively expensive green rooftop instead of a cheaper traditional model. In Section 2.5, the various economic, environmental, and social benefits of green rooftops are detailed. Section 2 as a whole attempts to give the reader an overall background of the problem and the intended solution and provide a platform from which to understand the methodology presented in Section 3.

2.2 Shortcomings of Traditional Rooftops

There are many contributing factors to pollution of the environment, but this paper focuses on the contribution of inefficient building design and construction, particularly that of roofing systems. The nature of current roofing systems of buildings in San Juan tend to cause both economic and environmental hazards including temperature pollution, pollution of water sources, high energy consumption, and excessive roof deterioration. The following sections examine how traditional roofs contribute to such hazards as well as the extent to which these hazards are present in San Juan and the rest of Puerto Rico.

2.2.1 Traditional Roof Structure

A roofing system has three main functional requirements: protection against precipitation penetration to the interior of the building, heat insulation, and load bearing capacity. Of all exterior surfaces of a building, roofs endure the most thorough beating from wind, rain, and the sun. These forces cause long term deterioration of the roof and its ability to insulate and repel water, resulting in costly repairs and unnecessary energy expenditures.

The heat from the sun and its ultraviolet radiation are the main ingredients that will deteriorate an asphalt based product, according to Carl D. Kuhn of Soprema Inc. (Breckenridge, 2004).

There are two types of roofing systems that are common in modern construction. The first type of roofing system and the most common variety used in San Juan is a built-up roofing system. This system consists of various layers, including a thermal insulating layer, a waterproofing layer, and a ballast layer usually consisting of gravel. The built up roof is usually placed in separate layers on top of the roof structural elements. An average asphaltic roof will last for about ten years, after which the roofing materials must be disposed of and replaced (Perry, 2003). This disposal and need for replacement incurs a high cost to both the environment and the building owner.

Another common roofing system utilizes an Ethylene Propylene Diene Monomer Membrane (EPDM). This system can be pre-made and delivered ready for installation or poured as a liquid on-site. This system is more expensive than the built-up system and can last up to 20 years (Personal Correspondence: Suffolk Construction).

2.2.2 Traditional Roofs' Contribution to Economic Difficulties

Roofing systems are built such that they will perform their intended function in the most efficient way possible. However, no matter how well designed the roof is, it will still conduct heat and moisture to the interior of the building. In the tropical sun, the exterior surface of the roof will commonly rise to over 170º Fahrenheit (Perry, 2003). As the temperature of the exterior surface of the roof increases, the rate at which heat is transferred to the interior also increases. Once inside, heated air puts a burden on the building's air conditioning system causing an increase in the building's energy demand.

Although it is difficult to show that a particular roof structure or that aggregate roofs in San Juan are performing inefficiently as opposed to an "ideal" roof, it can be shown that San Juan and greater Puerto Rico suffer from high energy consumption and an expensive energy supply. According to a September 2004 report from the Energy Information Administration, high oil prices have had an adverse effect on Puerto Rico's economy and inflation rate over the past year. Imported oil, mainly from U.S. and Caribbean suppliers, is the source of about 93% of Puerto Rico's power. In addition, power consumption across Puerto Rico is increasing at an average of 3% per year over the last decade (Puerto Rico Fact Sheet, 2004). Since there are no signs of a decrease in the cost of energy used to keep Puerto Rico's residents and workers cool throughout the year in the hot cities, few options are left. Puerto Rico has attempted to alleviate energy costs through exploration of alternative energy sources such as gas and coal (Puerto Rico Fact Sheet, 2004) and waste incineration (Miranda and Hale, 2005), but no significant immediate reduction in costs is apparent.

2.2.3 Traditional Roofs' Contribution to Pollution in San Juan

When an area is developed extensively, the aggregate effects of the replacement of natural surfaces can be very harmful to the environment. The San Juan Metropolitan Area is an example of such a region. It occupies roughly the same land area as Boston, Massachusetts, and is very similar in population density. Figures 1 through 3 show the population, land area, and population density for San Juan and Greater Puerto Rico, according to the U.S. Census Bureau's 2003 report.

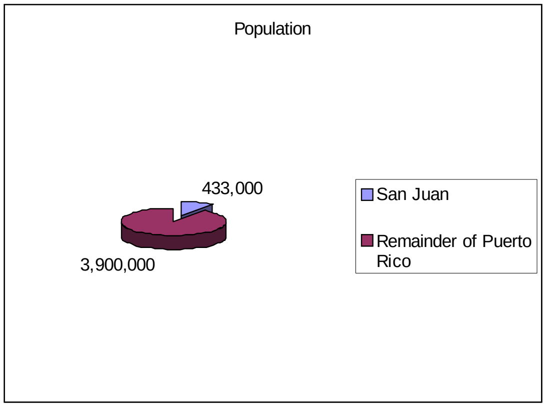


Figure 1 – San Juan's Population Relative to Greater Puerto Rico

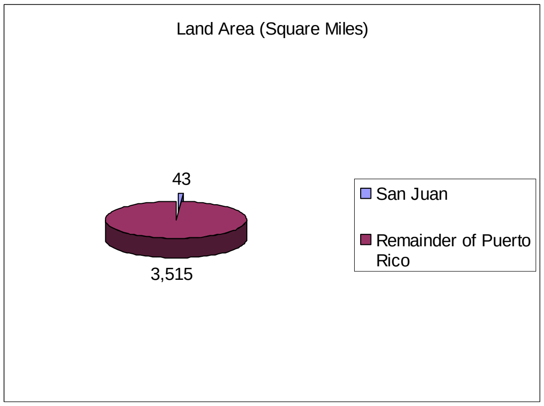


Figure 2 – San Juan's Land Area Relative to Greater Puerto Rico

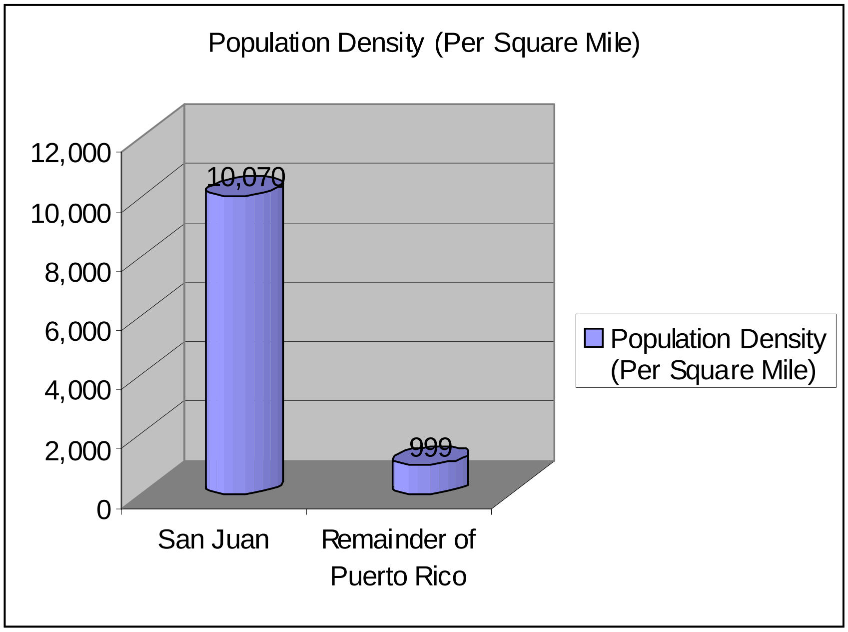


Figure 3 – San Juan's Population Density Relative to Greater Puerto Rico

The convenience of having a residence or business in an urban tropical location must come at some cost, and unfortunately, much of this cost is borne by the environment. The preceding sections have shown the shortcomings of traditional roofing systems and how they contribute to economic issues that exist in San Juan. The next few sections investigate the contribution of traditional roof structures to the pollution of Puerto Rico's environment, focusing specifically on temperature pollution and water pollution.

Alteration of Local Climate

It has been shown that a poor roof system causes an increase in temperature inside the building. In addition, because a building essentially replaces the natural soil and vegetation that used to occupy the site, the temperature of the local environment increases as well. Naturally vegetated areas have an intrinsic ability to cool themselves due to their water content. Evaporating water-cools natural areas in the same way that perspiration cools people, dissipating heat energy into the atmosphere as water molecules evaporate. In undeveloped areas, water is present within the vegetation and soil even during long droughts. In contrast, very little water is retained on urban surfaces, even shortly after a rainstorm. The dark pavement, huge vertical walls, along with expansive rooftops of the buildings absorb and reflect the sun, causing an increase in temperature in the city, known as the "heat island effect" (American Forests, 1995). The temperature in the city is typically 2-10°F hotter than the surrounding areas (Huber and Cappiello, 2003). A significant environmental change such as this is very detrimental to indigenous species and poses a legitimate danger to humans, including possible heat stroke and dehydration to all individuals, especially the elderly.

Puerto Rico´s climate has characteristics like most tropical islands due to the predominately easterly trade winds. However at night most of the winds shift to a south or southeast off-land breeze. This change gives the island its specific predominately unchanging climate, with average temperatures ranging only 5 to 6 degrees over the course of the year. Another notable phenomenon is the annual rainy season which occurs from September to March. Rainfall consists of mostly brief scattered showers taking place in the afternoon or evening, usually not more than an inch at a time, but sometimes up to 4.5 inches. The rainfall season tends to end abruptly in April, which averages the least amount of rainfall and the largest evaporation rate due to high temperatures making the already absent rain conditions even worse. Historical temperature data for San Juan and several areas close to San Juan suggest that San Juan does experience higher temperatures than its surroundings. According to www.weatherbase.com, using historical data from the past 40 years, the average temperature of San Juan is 80º Fahrenheit. For comparison, the smaller population center of Arecibo, located 48 miles to the west of San Juan and also on the northern coast of Puerto Rico, showed an average daily temperature of 75º Fahrenheit. A final comparison shows that Carolina, another small population center located only 10 miles southeast of San Juan, had an average daily temperature of 77º Fahrenheit based on 100 years of historical data. The locations of the three cities mentioned above can be seen in Figure 4. In a region that already has a relatively high average temperature, the heat island effect is at best a discomfort and at worst a severe health risk.

Figure 4 - Map Showing Relative Locations of San Juan, Arecibo, and Carolina (Weather Records and Averages)

Air Pollution

The loss of natural vegetation in urban development also poses other environmental hazards. Air quality decreases substantially when vegetation and its particulate-trapping and carbon dioxide absorbing ability is replaced with surfaces that literally pave the way for an increase in particulates and carbon dioxide. This, along with increasing fossil fuel consumption for transportation and power, can cause health problems, for example, it is estimated that in the United Kingdom alone, about 24,000 people die each year prematurely from the effects of air pollution (English Nature, 2003).

Water Pollution

Another environmental hazard caused by traditional rooftops is polluted storm water runoff and subsequent overloading of drainage infrastructure. When natural surfaces are replaced with impervious surfaces such as pavement and building rooftops during urban development, the water that would have been absorbed and filtered by a layer of soil must now be channeled into a municipal drainage network (English Nature, 2003). The drainage network is more often than not tied into the same system that carries sewer waste to a treatment facility. During periods of heavy rainfall runoff carrying pollutants and residues to the drainage system; such as hydrocarbons, silts, chlorinated hydrocarbons, oils, and heavy metals, can overload the treatment facility (English Nature, 2003). If this happens, there is no other option but to blow off the excess, sending untreated waste directly into the environment.

San Juan has been shown to cause significant pollution due to storm water and sewer runoff. Unfortunately, due to the rapid growth of the city in the past few decades, San Juan suffers from an insufficient sewage treatment plant facility, as new residents hook up to existing sewer lines (Hunter and Arbona, 1995). In a USGS survey completed in 1984, 54 of 67 river sampling stations exceeded the maximum microbiological contaminant level for recreational waters: 1000 colonies of fecal coliforms per 100 mL of raw water (Hunter and Arbona, 1995). The highest concentrations of fecal coliforms in surface waters generally occur in streams draining densely populated and industrialized areas of Puerto Rico (Osterkamp, 2000). This problem could be solved in several different ways, the most obvious and costly solution being a major restructuring of drainage systems so that storm water runoff and sanitary sewer systems are kept completely separate. Alternatively, green rooftop technology could be used to help alleviate stresses to existing infrastructure.

2.3 History and Implementation of Green Rooftops

The concept of plants on top of roofs is not a new idea, but the knowledge of its positive and constructive effects continues to increase as it is studied and evaluated. Green roofs have been gaining popularity in recent years. For the past 40 years, Germany and Scandinavia have led the surge towards the incorporation of green roofs. This idea and its use have been gaining more recognition throughout other parts of Europe, North America, and East Asia. Green roof technology has yet to achieve mass acceptance and use due to some appreciable obstacles. However, it has taken significant steps forward in recent years and evolved from a simple novelty to an emerging industry with significant economic and environmental benefits.

2.3.1 Green Rooftops in the World Today

Green roofs are being installed in increasing numbers all over the world. Some of the countries which have made efforts to adopt this technology include Switzerland, Germany, Japan, Canada, and the US. In Germany, seven percent of all new roof construction in recent years has utilized this technology, and over 140 million square feet of roofs throughout Germany are now green. In fact, green roofs are so popular in Germany that do-it-yourselfers can buy the materials to install a green roof at any major hardware store (Lamey, 2004).

Implementation has been slower in North America, but many cities in Canada such as Vancouver and Toronto have made strides to incorporate green roofs into new construction. In Vancouver, the proposed $535 million expansion of the Vancouver Civic Center features a six-acre green roof (Lamey, 2004).

Green roofs have begun to appear in the US as well. In Boston, the Ritz-Carlton Hotel and Towers off Boston Common has installed a green roof which has generated very positive reactions from the public (Reidy, 2004). Under Mayor Richard M. Daley's direction, the City of Chicago's Department of Environment took the initiative to start an aggressive green roof pilot project as part of that city’s Urban Heat Island Initiative with the United States Environmental Protection Agency. Completed in 2001, the project consisted of a 33,000 square foot vegetated roof using soil depths ranging from 3.5 to 24 inches (Roofscapes Inc., 2004 & Yocca, 2004). New York City and Washington, D.C. are among other U.S. cities that have seen installation of green roofs. Although no city in the US comes even close to the German statistics for green roof use, the current use and results in American cities are encouraging.

The green rooftop industry as a whole has enjoyed considerable success as the technology has gained popularity. It has achieved approximately 15-20% annual growth since 1982 (Industry Support, 2004).

2.3.2 Support from the Government and Special Interest Groups

Implementation of green roofs faces two difficult stumbling blocks: lack of knowledge and unwillingness of developers to pay the high initial cost. To combat these issues, support for this emerging industry has come from a variety of sources including special interest groups, ambitious and influential individuals, economic incentives and legislative mandates.

Green Roofs for Healthy Cities (www.greenroofs.org) is a non-profit industry association whose mission is to develop a market for green roof infrastructure products in North American cities. Its members include landscape architects, roofing and general contractors, materials suppliers, and governmental agencies. Groups such as GRHC work to disseminate information to a relatively unaware public about the advantages and possibilities of green roof construction (The Cardinal Group, 2004).

Another way in which the public has been informed of green roofs is through the dedicated efforts of influential and progressive individuals and governments who have specified green roof usage in planning objectives, such as the Urban Heat Island Initiative mentioned in the preceding section, or commissioned green roof projects as examples in hopes that others would follow suit, as in the case of Chicago's City Hall (Yocca, 2004).

The most significant obstacle to green roof construction is the high initial cost of the roofs. Often, developers are reluctant to make what is seen as an unnecessary and even foolish initial investment. In other countries, this barrier has been effectively addressed through economic incentives. In Germany, which boasts perhaps the most developed green roof industry of any country, over 50 cities offer economic incentives towards building green roofs. According to Osmundson (1999), 29 of these cities offer direct financial assistance ranging from about $0.50 to $5.00 per square foot. These incentives are significant when green roofs typically cost about $20.00 per square foot. The other cities offered indirect assistance, such as reduced sewer disposal charges for developments with green roofs (English Nature, 2003).

Although there are no direct incentive programs in the U.S., some cities have offered other types of incentives. According to Steven Peck, executive director of GRHC, both Chicago and Portland currently offer a density bonus for green roof development (Fantauzzi, 2004). This means that a developer would be permitted to construct more commercial or residential floor area on a site if the proposed building includes a green roof.

A final mode for encouraging the use of green roofs is mandatory legislation. Swiss federal law now requires all federal agencies to apply the 'Swiss Landscape Concept' when commissioning or rehabbing federal buildings. This program mandates that facilities must be compatible with natural settings and landscape. Swiss Law also requires 25% of all new commercial developments to be 'greened' in an attempt to maintain microclimates (English Nature, 2003). In Tokyo, any new construction project with a roof greater than 10,000 square feet must include cultivation on at least 20% of that area (Making Green Roofs Simple, 2003).

It is clear that in places where green roof construction has been most widely used, implementation has been aided through dedicated governmental incentive programs and legislation.

2.4 Green Rooftop Construction

The construction of green roofs can be complicated. There are two basic types of green roofs: extensive and intensive. An example of an extensive green roof is shown in Figure 5. Both types involve adding weight onto the top of an already existing roof. Soil selection is important, due to the variation in soil types. For example, a soil that is more than 20% organic would be a poor choice in rooftop applications because organic soil disintegrates quickly (Solomon, 2003). Often, a substrate is chosen that is specific to the desired application. Some materials typically used for green roofs include compost, sand, crushed brick, sand, gravel, and peat (English Nature, 2003).

Figure 5- Extensive Green Roof

After selection of the soil, the loading that the soil places on the roof must be considered. Saturated extensive green roofs may cause an additional loading ranging from only 15 pounds per square foot (psf) up to 100 psf, depending on the thickness of the sod layer (English Nature, 2003). A saturated intensive green roof can create a load of up to 200 psf, which includes an allowance for human use of the roof. Loadings this high will often strongly influence the design of structural members. However, many buildings that are several stories high are already equipped with the heavy steel or reinforced concrete, and often have the capacity to handle the loads mentioned above. Even for those buildings that would need additional bearing strength, it is fairly easy to add the additional weight-bearing capacity to a new building (Breckenridge, 2004). Shorter low-rise buildings are where a problem will come into effect if an intensive green roof is desired. There may be a need for a greater load capacity and substantial structural reinforcement.

2.4.1 Extensive Green Rooftops

Extensive systems have a thin layer of soil, typically ranging between 3 to 6 inches. This soil can only support low growing vegetation. Due to its light weight, this type of roof can usually be placed directly on the existing roof. Therefore, it would prove to be the most practical and economical green roof system (Solomon, 2003).

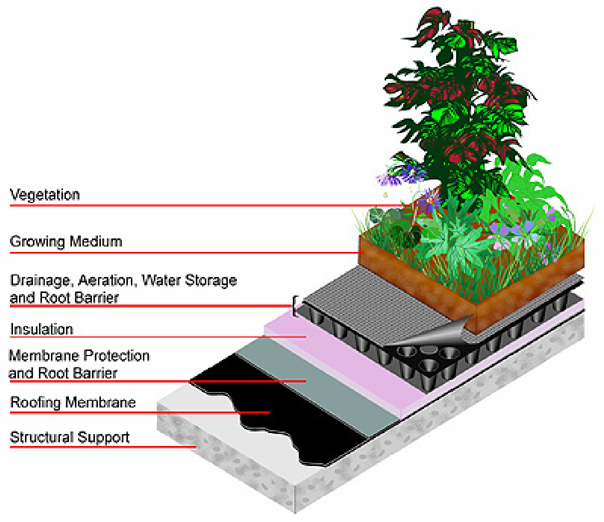


Figure 6- Diagram of Typical Extensive Planting Setup

Though there are a number of different variations of the extensive system, they all have certain components in common. From the bottom upward, the first layer contains the waterproofing membrane, followed by a root barrier, which keeps the plants from damaging the membrane. Next, a combined drainage and water retention layer stores water through drought periods and drains excess water during periods of extended rainfall. A filter fabric between the soil and the drainage layer prevents soil from clogging the drainage system, while allowing the roots to reach the water below. The very top parts are the layer of soil, and finally, the plant life on the surface (Perry, 2003). A typical layering setup is shown in Figure 6.

2.4.2 Green Rooftop Vegetation

Several types of vegetation are used in extensive green roofs, including mosses, succulents, grasses, and wildflowers (English Nature, 2003). Plants used for roofs must be able to handle various climatic conditions. One of the most favorable characteristics of plants used in green roofs is drought resistance. This is certainly the case in San Juan, as it may be months between rainfalls. Drought resistant plants are easily identifiable. These types of plants often have stout, leathery, succulent, or waxy foliage (Cundall, 2004). The most common plant used is *Sedum*, a low-growing succulent known by the common name of stonecrop. As its common name suggests, it is a hardy plant that does not require much maintenance or irrigation. There are many different types of *Sedum*, and each has its own characteristics and climatic preferences. Some types can live almost a month without water, making it a good choice for use on green roofs. In addition, *Sedum* propagates quite readily, as almost any tiny piece of the leaves or stem that touches the ground will sprout leaves (May, 2001). Different types of *Sedum* are available based on the climate and soil conditions. Some include the lower growing Sedum, yellow flowering *Sedum acre* and white *Sedum album*, or the taller *Sedum*, *Sedum rupestre*. *Sedum acre* is one of the most commonly used types of vegetation for extensive green roofs (West, 2004). A list of several types of *Sedum* as well as other types of drought-resistant plants and their brief description is given in Figure 7.

Name of Plant	**Drought Tolerance**	**Moisture Tolerance**	**Heat Tolerance**	**Height**	**Description**
Sedum spurium ‘Fuldaglut’	Very Good	Fair	Good	6”	Reddish green foliage with pink flower
Sedum acre ‘Aureum’	Very Good	Good	Poor	3”	Green foliage with yellow flower (See Figure 8)
Sedum sexangulare ‘Tasteless Stonecrop’	Very Good	Fair	Fair	6”	Green foliage with yellow flower (See Figure 9)
Achillea tormentosa ‘Alpine Milfoil’ ‘Wooly Yarrow’	Very Good	Fair	Fair-Poor	5”	Yellow flowering plant thrives in rocky crevasses
Felicia amelloides ‘Blue Marguerite’ ‘Kingfisher Daisy’	Good	Fair	Fair	1.5’	Displays masses of sky blue daisies on woody stems.
Sedum rubrotinctum ‘Pork and Beans’	Good	Fair	Fair-Poor	7”	Fleshy green leaves with reddish yellow flowers in winter (See Figure 10)
Talinum calycinum	Good	Poor	Good	12”	Green foliage with purple flower. Spreads around other vegetation but is non-aggressive.

Figure 7- Chart Showing Possible Plant Species (Emory Knoll Farms, 2005, Desert-Tropicals.com)

Figure 8 - Sedum acre (Desert-Tropicals.com)

Figure 9 - Sedum sexangulare (Desert-tropicals.com)

Figure 10 - Sedum rubrotinctum (Desert-tropicals.com)

2.4.3 Intensive Green Rooftops

Intensive systems require a layering system similar to that of extensive systems, however these systems utilize larger plants with deeper roots. This requires a substantially deeper soil layer. While being much more visually attractive than extensive plants, they may require that the roof be restructured due to the added weight of the soil. Intensive systems also need regular maintenance and irrigation. These roofs are intended for humans to enjoy, but incur a high installation and maintenance cost. In addition, the fertilizer, a necessity for faster growing plants, can slowly seep into the water systems, and therefore harm the ecosystem. Intensive roofs require a higher investment of time and money, but they also offer a green space for people to enjoy, are typically better at insulating the building than are extensive roofs, have a higher storm water retention capability.

2.4.4 Pricing

Initial costs of a green roof range from three to six times more expensive than that of a traditional roof. Current U.S. prices for extensive roofs range from $14 to $19 per square foot. However in Germany there is an entire industry built around green roof installation, which considerably decreases the initial cost. In the U.S., it can be expected that the costs of materials and installation will decrease significantly if an industry develops. As a green roof industry in the U.S. matures, prices will decrease to a range from $8 to $14 per square foot as they did in Germany (English Nature, 2003). Figure 11 shows a life-cycle cost analysis for green roofs. This model considers installation and replacement costs over a 31 year period. It does not include energy costs.

Life Cycle Cost Analysis
Comparing three 25,000 sq. ft. roofs in the 31st year of use.

Roof #1 -A Three-Ply, Asphalt BUR roofing system with a price of $9.00 per sq. ft. Average life expectancy 10 years.

Roof #2 -A Modified Hot applied roofing system with a price of $10.00 per sq. ft. Average life expectancy 20 years.

Roof #3 –A Two-Ply Modified Bitumen, Green roofing system with a price of $12.00 per sq. ft. Average life expectancy 40 years.

	Roof #1	**Roof #2**	**Roof#3**
Initial Capital Expense	$225,000	$250,000	$300,000
Capital Expense/Inflation In year 31	$1,154,595 (replaced 2x)	$591,764 (replaced 1x)	$300,000 (original roof)
Maintenance Costs/ Inflation In year 31	$26,607	$26,607	$26,607
Life Cycle Costs In year 31	$359,682	$283,939	$270,447

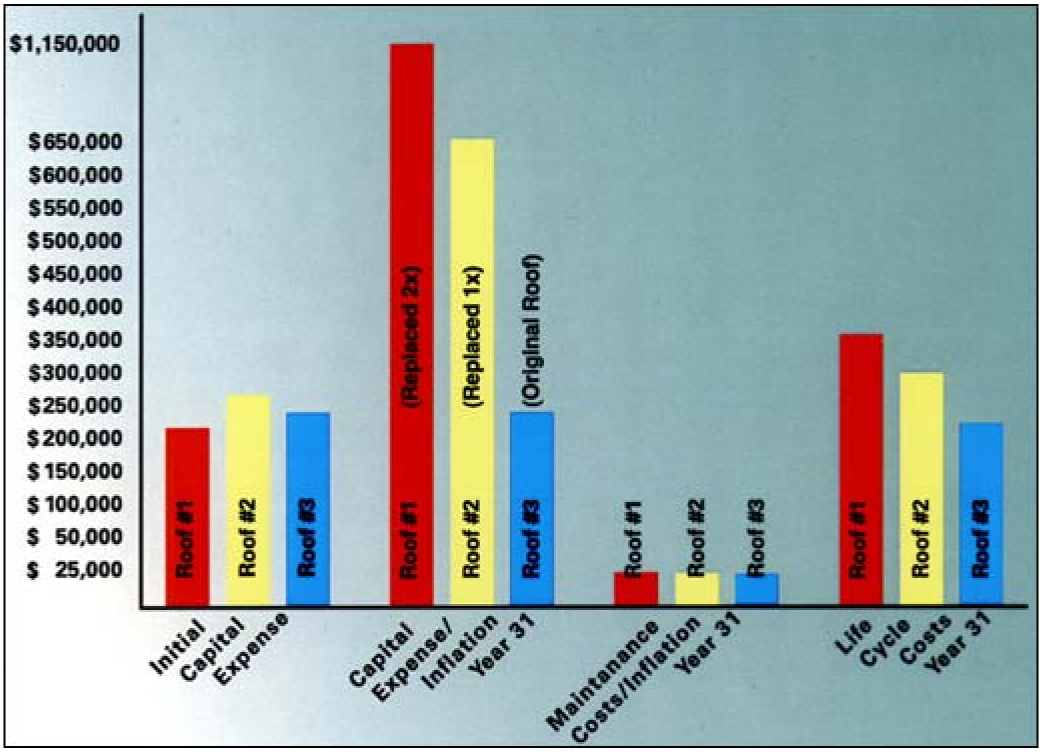


Figure 11 - Life-Cycle Cost Example (Korote, 2003)

This chart was created based on a 31 year look at the cost benefits of a life cycle, of a

25,000 sq foot roof constructed under three different systems. According to this cost analysis of the roof it will pay for itself in the long run. In addition, the owner of the green roof will enjoy the added benefits of an annual savings of 10% to 20% of energy usage, thus shortening the time period over which the building owner pays off the initial costs of the green roof (Korote, 2003). Another study done by an American Society Heating Refrigerating and Air-conditioning Engineers simulation showed that the city of Chicago, after completing a renovation of green roofs to the whole city would save an annual cost of $100,000,000 (Peck, 2000). According to this information, the life cycle of a green roof seems to be an extraordinary option for communities to save energy and help protect the environment.

2.4.5 Conclusion

A practical and inexpensive solution to the environmental problems of Section 2.2.3 is the extensive green roof system. As stated above, there usually doesn't have to be any restructuring of the existing rooftop, nor does it have a negative affect on the environment. Extensive rooftops can be very appealing and functional without the extra expenses associated with intensive rooftops. Life-cycle cost analyses have demonstrated their favorable performance against traditional roofing systems even without accounting for their energy saving and environmental potential.

2.5 Technical, Environmental, and Aesthetic Value of Green Rooftops

Most modern cities are a sea of black, gray and brown structures. The greening of rooftops, or roof gardens, makes sense on many levels. The most obvious appeal is the aesthetic value of seeing greenery added to the urban landscape. However, the green rooftop possesses many technical and environmental applications that are presently being implemented in many European countries and are becoming increasingly popular around the world. In this section we will review the positive aspects of a green roof.

2.5.1 Reduce Runoff

One of the green roof's many positive environmental attributes is its ability to retain rainwater, which reduces runoff. In urban areas, runoff occurs when rainfall hits hard, nonporous surfaces like rooftops or pavement, and runs off into storm water holding facilities and nearby bodies of water (Osmundson, 1999). The layers of soil and vegetation which comprise a green roof absorb and hold rainwater like a sponge. Previous studies in Berlin have shown that green roofs are capable of absorbing 75 percent of rainfall that falls onto them; the result is that immediate discharge is a quarter of normal discharge levels (Johnston and Newton, 1993).

Short, intense bursts of rainfall can cause runoff to quickly overload sewer systems, posing a host of environmental and public health threats. "In older cities….a heavy downpour of a half inch (a centimeter) or more causes sewage to overflow into the storm tunnels leading directly into nearby waterways….Roof gardens can help alleviate this problem by serving as a kind of water retention system" (Osmundson, 1999). A green roof will collect and retain the rainwater, and release it at a slower rate (EPA, 2000). By implementing a wide network of green rooftops a city could reduce the demands on its storm-runoff system, curb sudden floods, and improve water quality in nearby waterways.

2.5.2 Building Efficiency

High temperatures and population densities can cause excessive demands on the power grid of many areas due to increased air conditioning needs. Roofs are one of the main mediums for heat transfer in modern buildings (Osmundson, 1999). Insulation is used to reduce heat transfer through roofs, and green roofs can increase the insulation value of a roof up to 10% (Johnston and Newton, 1993). The Newton Valley Winery in Napa Valley uses a roof garden to keep their barrel storage room cool. By using 4 feet of soil they are able to keep the room cool without the need for air-conditioning (Osmundson, 1999). The added insulation of a green roof system presents an opportunity to reduce energy demands.

The vegetation of a green roof helps reduce the surface temperature by absorbing solar energy by transpiration and photosynthesis, both vital processes for plants, as well as reflecting a portion of the sunlight (Osmundson, 1999). In a field study it was found that on a particular day a bare roof reached 57°C and a roof covered with soil reached 42°C. Many varieties of plants were used, but the maximum temperature reached by a roof covered by vegetation was 36°C, the minimum, 26.5°C, was recorded under a Raphis palm, a dense shrub (Wong et. al, 2002). This study proves that vegetation on a roof actively reduces a building's summertime temperature.

A green roof both insulates the roof and acts as an air conditioning pad because "It sweats, and essentially becomes an evaporative cooling system" (Primeau, 2003). By these two methods a green roof can help reduce the heat transfer in and out of a roof. In some cases a green roof can lower cooling costs by as much as 10% (Breckenridge, 2004). In the search to find ways to make buildings more efficient a green rooftop should be considered.

2.5.3 Heat Island

The solid walls and pavement of most cities are the leading cause in a local temperature increase known as the heat island effect (American Forests, 1995). Green roofs provide an excellent way of replacing the vegetation that was lost to urban sprawl (Solomon, 2003). By reflecting the sunlight and through the evaporation of water through transpiration a green roof can lessen the heat island effect. If a portion of the roofs in a city were green roofs, the temperature could be reduced by several degrees (Osmundson, 1999, 31).

Green roofs can also help reduce the urban heat island effect by promoting air circulation. The air above vegetation is generally cooler than the surrounding air, so by the laws of heat transfer the hot air will replace the cool air causing circulation, which will cause a decrease in ambient temperature (Johnston and Newton, 1993, 11).

A field study by Wong et al. (2003) explored the temperatures directly above both green roofs and regular roofs. It was found that during the night the temperatures for a green roof and regular roof were very similar. However in the afternoon the temperature of the ambient air above the green roof was found to be much less than that above the solid roof. This indicates that the green roof actively cooled the surrounding air to create this temperature difference (Wong et al, 2003). If the air at night is cooled faster over a green roof, than it will be cooler in the morning and take longer to heat up, reducing the heat island effect.

2.5.4 Roof Protection

A practical aspect of a green roof is its ability to prolong the life of the roof. Roof vegetation offers protection from the sun's damaging ultraviolet radiation (Johnston and Newton, 1993). Although the hot sun causes significant damage to traditional roofs, the winter season is also capable of eroding and fracturing roof surfaces with ice and snow. Green rooftops have been shown to reduce or eliminate the damaging effects of wintertime conditions as well (Johnston and Newton, 1993). The life of a green roof can significantly outlast that of a traditional roof while maintaining its original quality; one green rooftop installed on a department store roof in Britain in 1938 was examined almost 50 years later and the roof surface was found to be "still in excellent condition" (Johnston and Newton, 1993).

Despite such successful cases, a persisting misconception about green roofs is they can cause roof damage and make repairs difficult. "A lot of people shy away from the idea because they think there'll be water leaks in the house or that the roots will grow inside, but none of these things are going to happen" (Primeau, 2003). The vegetation and soil layers do not threaten the roof's integrity. Instead, they serve to protect and prolong the life-expectancy of the roofing materials on which they are placed.

2.5.5 Aesthetic Value

For centuries the idea of a living structure has captured the imaginations of humans throughout the world. From the Hanging Gardens of Babylon to the sod roofs of Europe to the cities of today, desire to combine shelter and vegetation has remained. Some examples of this combination are simply for visual pleasure, while others can be very functional. In today's world of expansive, high tech buildings is there a need or desire to incorporate plant life into structure? Most people believe, for many reasons, that yes, vegetation should be a key part of modern buildings. Nearly every new building built today has a portion of the budget, in many cases a large portion, devoted to landscaping. Small trees and shrubs are planted to make the building more attractive and welcoming to its users or inhabitants. Relaxation and a feeling of a vacation are connected to these environments. People tend to want to get away from their industrialized work environment, and travel to the 'real natural' environment tucked away in the hills or on the shores of a calm lake. Not many people want a home, fourteen stories above the busy, smog filled streets of a large city. In this sense the ideas of green roofs jump out as the perfect idea for a community that is largely based on the tourist industry. Beautifying the island or the major metropolitan area of San Juan would not only be a solution for energy, pollution, and heat conditions but it would have a visual stimulation to augment the overall experience of Puerto Rico. A city adorned with vegetated roofs would nicely complement a tourist destination known for its sunny beaches and tropical rainforests.

2.5.6 Conclusion

While there are a few areas where a normal roof will function better than a green roof, a green roof can perform as well or better than a normal roof in the majority of cases. A healthy green roof will not only look great, but can improve many aspects of a building. The green roof is an excellent option for many of today's buildings as it can be easily integrated to improve the appearance and function of the building. Although there are many more aspects of green roofs to explore, the potential for visual impact as well as positive characteristics make green roofs an interesting new combination of vegetation and structure, which will hopefully gain popularity in the near future.

Green rooftop construction helps to alleviate some of the threats that cities pose to the environment. This technology has the potential to yield significant benefits to society, such as reduction of the urban heat island effect, reduction of demand for increased drainage capacity, and reduction of energy demand due to insulating effects. San Juan has been shown to suffer from all of the problems which green rooftop construction may help to alleviate, and it seems that the trend is for these problems to worsen. Green rooftop construction provides a way for the residents and businesses of San Juan to help pursue sustainable development, ease the strain placed on the environment, and help ensure the beauty of the city and the environment will be enjoyed by future generations.

3 Methodology:

This project is intended to help the residents and businesses of San Juan to decrease the economic and environmental costs of living and doing business in the San Juan Metropolitan Area by exploring the feasibility and desirability of implementing green rooftop technology. As stated previously, green rooftop technology has existed for years and successful support industries have been developed in other regions of the world such as Germany. The technology has been proven to be effective in climates such as Germany's, but it has not been proven in tropical latitudes (Personal Correspondence: Ángel David Cruz). Even studies that have proven the effectiveness of these roofs in other regions may not be enough to convince building developers to fund the high initial cost of such roofs. Thus, a local study is needed that proves these benefits in Puerto Rico's climate.

The team determined whether or not this technology could be effective in San Juan's tropical climate and investigated the attitudes and needs of potential buyers of green rooftops as well as those who would be involved in the design and construction of them. We then prepared recommendations for continuing the study of green roofs and moving towards the ultimate goal of developing a green roof industry in San Juan.

3.1 Analysis and Reconditioning of Existing Green Roof

The green roof that we encountered at the University of Puerto Rico was a fading project in need of substantial reconstructing. Lack of rainfall and maintenance had taken its toll on the roof in the harsh conditions of a tropical climate. This however presented an interesting opportunity and a challenge to investigate the original plants' ability to survive under extreme conditions. An observational period over several days was set up to investigate and analyze past documents in comparison with the rooftop's current condition in the following steps:

- Translation of the documents and faxes from the Institute for Agrarian and City-Ecological Projects at Humboldt University, from German to English providing information on the original green rooftop layers, plants, and plant spacing.
- Using translated information to compare to existing roof; looking for plants still existing and current plants which had taken over.
- Actual deconstruction of small parts of several layers to understand their physical make up.
- Comparing the soil and substrate observations with plant's survival and overall growth on original plots.

Upon analysis approximately 60 percent of the roof's original vegetation was completely gone. Results through an experiment showing values of energy saved through heat transfer would not be effective on a dirt roof. Rejuvenating the roof became necessary so that accurate data could be read by the temperature sensor network. Temperature readings could not be taken until sufficient living ground cover developed. This occurred after a period of three weeks, through extensive reconditioning as outlined below:

- Selection of the best sections to do our testing based on our results from the analysis of the roof.
- General cleanup of the rooftop, weeding excess plants and shrubs which are foreign and have potential to grow taller than wanted.
- Reseeding of grasses by composting the dead plants and spreading their seeds.

- Restoring lost soil along with spreading fertilizer (see below for in-depth explanation).
- Watering the plots on a regular schedule (refer to Appendix B for records).

Water, although vital, is not the only necessity for survival and success of our vegetation. Nutrients are vital not only in the developing stages of a plants life cycle but also in maintaining its overall growing ability and health. The three most essential elements present in soil are nitrogen, phosphorus and potassium. Each element gives vegetation help in different ways. Nitrogen is the main nutrient, the vitamin of plant life, which helps the formation of chlorophyll within the plants. Phosphorus assists root development while potassium facilitates the overall health and abilities of the plant. The correct combination of these nutrients is important to healthy vegetation. These three main elements are the bases for fertilizers and are in ratios on the front of brand name products. For our plants we are using a 17-17-17 fertilizer which is a turf fertilizer and good for our low growing plants, and will slowly release over the next few months.

3.2 Initiate a Long-Term Study of Materials

This section outlines the methods by which we determined which plants and soils should be examined for use on green roofs in San Juan. It also shows the process by which we developed a long term experiment for these items.

3.2.1 Investigation of Plants and Availability

By consulting with Puerto Rican nurseries and plant experts we compiled a list of plants that provided adequate characteristics for a green roof that also fare well in the Puerto Rican climate. We first began by contacting Dr. Eugenia Santiago, a professor in the Biology Department at the University of Puerto Rico. Dr. Santiago is a botanist and therefore was very knowledgeable of our topic. We also received several reports conducted by the Polytechnic University of Puerto Rico from a contact there, Mr. Ismael García Ortega. One report investigated plants under the guidance of Mr. Vicente Quevedo and the other investigated soils under the supervision of Mr. Gilberto Acevedo Ramos. Information from these were mainly used to figure out availability of plants.

We identified 24 nurseries and landscaping companies in the San Juan area to visit, and interviewed the owners, who were familiar with locally available plants. Being professional gardeners or landscapers and working with plants everyday gave them the information that we needed. They gave us a list of plants that might work on the roof and were available. In order to get in touch with these nurseries the first task we had to complete was to search through the phonebook for different places to call. We had to look at categories such as landscaping, gardening, and plants with an end result of 24 stores. We then found out where these nurseries were located in order to visit them and cut down the number of possibilities. We called the nurseries and spoke to them and visited others. Many of the people we talked to did not speak English well enough to find out the information that we were looking for. Eventually we had 5 nurseries we used to get our plants.

We developed key contacts including Mr. Tomas Aponte of Pennock Growers and Mr. Ed Snodgrass of Emory Knoll Farms. Mr. Aponte was able to offer us four plants which we might be able to use. Mr. Snodgrass an expert in his field is usually paid for his help on projects but helped us out on the circumstances that we keep him informed throughout our project. He sent us a list of 8 plants to try that he thinks will work well in tropical climates. We compiled a list of advantages and disadvantages for each plant because there are certain plants that fit better for certain circumstances than others. Once we had received all our information we then determined the best plants for a green roof in Puerto Rico. After finding where all these plants could be found we bought them, which we then planted in a series of experimental plots.

3.2.2 Investigation of Substrates and Availability

Information was obtained after we talked with two very knowledgeable professors within the University system. Dr. Eugenia Santiago, as mentioned before, helped us with not only the plants but also the substrates, along with Dr. Miguel A. Muńoz, a Soil Chemistry and Mineralogy researcher at the agricultural experiment station branch of the University of Puerto Rico. Through these meetings we came up with several things that must be present in our growing layers and ideas of what to use.

Absorption of water by our soils is necessary, along with aeration to sustain living roots for the vegetation. Some soils will retain a great deal more water than others, which in turn provides a longer time that the plant can exist without rain. This water retention is needed, but there can not be a compaction of the soil or there will be a supersaturating of the soil and no drainage for the roots. Our process has led us to the substrate material best suited in our extensive roof as a material of mid grain size and of the rock form which will retain water at the same time have resistance to compaction and can contain a larger air volume. Volcanic rocks present on the roof are a very feasible option due to properties comparable to the properties listed above. Other options that are being investigated consist of crushed brick which is already used in parts of the green roof market in the United States and another idea that has not been investigated yet is limestone. Considering these options the base needs to be big enough so that the plant will not up root easily in the heavy rainfall or tropical storms, so depth will come into our selection as well.

Within our research for feasible soils these two main points must be looked into to help the life cycles of our self-maintaining plants. A soil that is able to maintain nutrients and release at a steady rate, retain water, and not deteriorate is a perfect combination. Ideally a green roof built in Puerto Rico would use the materials specified for use in Germany or other countries where green roofs are popular. However, effects of the materials need to be proven to have the equivalent proven benefits in the drastically change climate. Working around this problem to achieve a viable option, we have asked the same contacts and nurseries when looking for plants if they have any soil options that will meet our needs of the suggested essential items from our Professor’s opinions.

3.2.3 Experimentation

Once all of the plants and the soils were determined, we had to use our experimental blocks of roofing. This gave us the opportunity to test 3 different soils and 8 different plants in the nine available blocks. As well as watering the rest of the green roof we recorded information everyday on its development. We will determine from this which plants work best in what type of soil. We will also be calculating the heat loss, water runoff, and the cost of each, based on how much the materials including plants cost.

3.3 Feasibility Study for Green Roofs in San Juan

The effectiveness of green roofs has been proven in other areas of the world, but it is unknown whether or not green roofs can be effective in a tropical climate such as that of San Juan. There are two ways in which we assessed the effectiveness of green roof technology. We first examined green roofs from an individual perspective and then looked at green roofs from a societal standpoint.

In order to examine the effectiveness of green roofs in San Juan from the individual (micro) perspective we developed a life-cycle cost model which compared the performance of green and traditional roofs over a 40-year time frame. This time frame was chosen because green roofs have been observed 40 years after their installation to be in excellent working condition. The model incorporated installation, maintenance, and replacement costs as well as energy costs for both roofing systems. It attempted to show that despite their high initial cost, in the long run green roofs would more than pay for themselves.

The macro model investigated the benefits and savings to society that would occur as a result of more widespread implementation of green roofs. The purpose of the development of this section was to alert environmentalists and policymakers to the societal benefits of the green roofs that their incentive programs could one day encourage. This information will be useful in presenting the advantages of green roofs to policymakers. In order to obtain data for the cost analyses, we had to develop a temperature sensor network.

3.3.1 Temperature Sensing Network

The main goal of our temperature sensing network was to provide hard data to assess the benefits of green rooftops. Originally we had planned to set up a permanent large scale network that would be in use at all times, but due to issues such as cost and the design of the roof we had to rethink our plan. We used a more temporary network which could be reconfigured easily to perform several different functions. This network consisted of three main components: the sensors themselves, the computer based data acquisition hardware, and the software to manipulate the data to give us the desired output.

Sensors

We used thermistors to take the temperature measurements on the roof. A thermistor is basically a resistor whose resistance changes as the temperature does. The temperature resistance relationship of a thermistor is presented in a graph or equation by the manufacturer. We were able to acquire 10 5K3A1A general purpose thermistors from Betatherm Sensors in Shrewsbury, MA. Each sensing unit consisted of the thermistor, another resistor, the battery holder and the lead wires which go to the computer. Everything was configured as shown in figure 13.

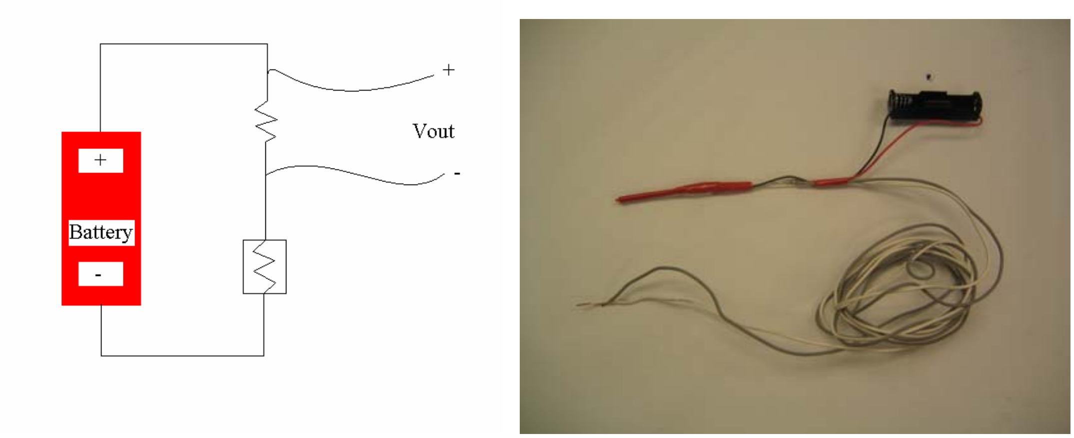


Figure 12 Schematic of Probe and Photo of Sample Probe

Using the principle of voltage drop over a series of resistors we were able to determine the resistance of the thermistor by measuring the voltage across the other resistor.

Data Acquisition

We need a way to take the signal supplied by the sensor and convert it into useful information. We used two Measurement Computing PMD-1208LS, shown in figure 14, portable data acquisition devices to accomplish this. The PMD-1208LS interfaces with a computer through its USB port. It reads the voltage from the sensor, converts it into a digital signal, and sends it to the computer where it is processed by the software.

Figure 13 PMD-1208LS Data Acquisition Device

Software

Once the signal is sent to the computer it needs to be processed to give us the data we need in a way that can be easily manipulated. We used Labview, a program from National Instruments that can be set up many ways to accept and manipulate sensor information. We created a program which takes the four voltage inputs from the DAQ hardware and manipulates it to give the temperatures of the sensors. It also outputs the temperature data to a spreadsheet so we can use it later. Below in figure 15 is how the front panel of our program looks.

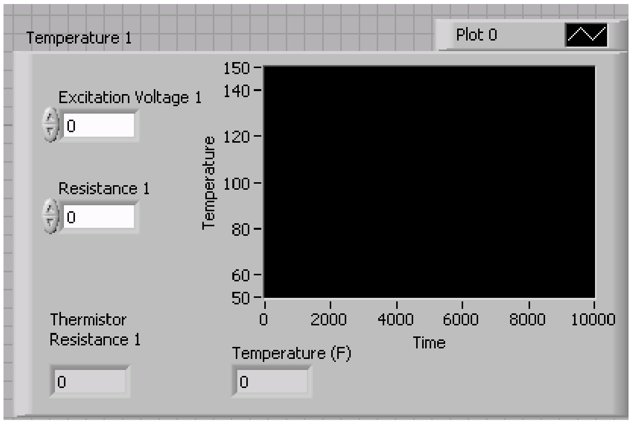

Excitation Voltage 1: 0
Resistance 1: 0
Thermistor Resistance 1: 0
Temperature (F): 0

Figure 14 Example of Software Display

3.3.2 Micro Cost Analysis

The first step in developing the lifetime cost analysis model was identifying all the materials, activities, and processes that incur costs on both the traditional and the vegetated roof. Both roofing systems incur installation costs and costs associated with heat transfer through the roofing system. Costs specific to traditional roofs also include periodic replacement over the 40 year time frame. Costs specific to the green roof include costs due to increased structural loading of green roofs and annual maintenance costs. Only direct monetary costs were assessed in the micro model. Costs that were left out of the model include costs borne by the environment such as various types of pollution resulting from the different roof structures. These costs will be dealt with in part in the macro analysis.

The monetary costs had to be quantified and located in time. For both the traditional and green roof, a large part of the cost is incurred when the roof is installed. However, many costs are incurred at some later point during the lifetime of the roof. These costs include maintenance, replacement, and the cost of energy needed to condition the air that is subject to heat transfer through the roof.

Installation Costs

The installation cost is the first cost incurred in the life-cycle cost analysis. The cost of constructing a green roof is significantly higher than the cost of installing a traditional roof, since they are so much more complex than traditional bituminous roofs. The cost of building a green roof in Puerto Rico is currently unknown because there has only been one green roof built there, and an analysis of existing conditions reveals that it is not up to the current industry standard. Please see Section 3.1 for a description of the shortcomings of the green roof at the University of Puerto Rico.

The costs of constructing a traditional roof were obtained through fax communication with local roofing contractors and by procuring unit area costs from RSMeans based on a 10,000 square foot roof. Boston-based Suffolk Construction also provided insight into roof construction and cost. A description of the different traditional roofing systems can be found in the background section. A listing of the companies consulted, the unit-area price quotes, and the respective type of roofing system is provided in Results Section 4.4.1.

To determine green roof installation costs, we looked into several leaders in the green roof construction industry in the United Kingdom, Canada, and the U.S. These companies offered a wide range of information, from detailed specifications and cross sections of the different assemblies to general square foot costs for their extensive roofing systems. These figures were beneficial because they gave us a good idea of the nature of cost involved with constructing a green roof in San Juan. However, they do not account for the differences in climate and available materials between San Juan and the areas where green roofs are popular. Other information that was provided included itemized breakdowns of manufacturing and installation costs for individual components. These allowed us to get closer to the actual cost of a green roof in Puerto Rico. Because the costs were broken down to individual items, we were also able to substitute locally available materials and plants easily.

A green roof is a complex assembly of different materials. Some of the materials used in green roofs are commonly used construction materials, such as insulation, root barriers and waterproofing materials. Other materials are location specific, such as substrate materials and plant species. For maximum efficiency, a green roof should incorporate materials that are locally available. Thus, we investigated locally available plants and substrates and substituted their costs for those of comparable materials quoted by foreign companies. Please see Section 3.2 for a description of the San Juan-specific plant and soil selection process.

Other materials, such as the drainage and water retention systems, are highly specialized for use with green roofs. Each company we consulted uses a uniquely developed system, and procurement of these materials for use in San Juan would incur high shipping costs. In order to build a green roof in the near future in San Juan, one would have to account for these costs. However, for a more valuable long-term analysis, it seems reasonable to assume that a local manufacturer exists that can produce these unique layers at a comparable cost to those encountered among existing companies.

The names of the companies from which we obtained prices were found in newspaper and magazine articles about green roofs and a listing of participants at a green roof convention that is to be held May 4-6 by Green Roofs for Healthy Cities in Washington, D.C. A listing of the overall square foot costs of these green roofs and an itemized cost breakdown of the materials is located in Results Section 4.4.1.

Cost of Maintenance and Repairs

There is no real standard maintenance involved with traditional roofing systems. Instead, they are left to deteriorate through their life cycle and then are replaced. In order to determine replacement costs, we consulted records at the University of Puerto Rico. We also consulted with Puerto Rican roofing companies to determine the life expectancy of the roofs which they proposed to install.

In order to ensure proper functioning of green roofs, routine maintenance must be performed. Information on the types of maintenance required was obtained through Alumasc-ZinCo's brochure entitled "Green Roof Systems." It explains that when left neglected, the water-retentive green roof vegetation will be taken over by dominant indigenous species and the green roof will not function properly. In order to assure proper functioning, grassy extensive green roofs should be trimmed and mowed and unwanted alien vegetation should be removed once a year. In addition, during extended periods of drought, the use of a "drip" irrigation system may be considered (Alumasc-ZinCo, 2004).

There may also be maintenance costs associated with intense initial care of an un-established vegetative layer. Although some green roofs are planted and seeded, thus needing this initial care, many extensive green roofs are laid down as a pre-grown sod mat. For this analysis, this type of maintenance will be included in the installation cost, since it is not a routine maintenance objective.

Structural Costs

One final material-related cost that needed to be considered was the increased cost of structural members due to the increased loading that results from installation of a green roof. Existing buildings may or may not have sufficient structural capacity to support a retro-fitted green roof. Each building would have to be individually assessed by a structural engineer in order to determine their ability to bear additional loads.

The cost of additional bearing strength is difficult to quantify because it can vary greatly from building to building, according to the particular building's height, floor area, and pre-existing design loads on the building, among other variables. The best that can be done in this study is to assume an "average" building with typical design loads, and to use typical preliminary design assumptions to determine the relative increase in cost due to the added weight of a green roof.

We first had to determine by how much a green roof would increase the loading on a normal roof. Within this objective, the first step was to determine a rough traditional roof loading. The dead and live loads that must be supported by a traditional roof are listed in Figure 16. The loads used here are very general. In today's design procedures, a much more rigorous approach must be given to accounting for structural loads. In addition, safety factors must be used to scale the given loads. However, to find the percentage increase in total weight due to the weight of green roofs, it is not necessary to use safety factors.

Item	Description	Load (Pounds per Square Foot)
Concrete Deck	6" Slab, 150 pounds per cubic foot concrete	75
Roofing, Mechanical, and Ceiling Materials	Roofing Materials, HVAC Equipment, Ceiling Tiles	10
Live Load	Maintenance Crew	30
Total Load		**115**

Figure 15 - Structural Loads for Traditional Roof

The installation of a green roof subjects the roof to additional weight. A green roof would have to support all the loads that the traditional roof supports, plus the weight of the additional layers, soil, and plants. Figures 17 and 18 show sample green roof assemblies and their respective additional loadings.

Item	Description	Load (Pounds per Square Foot)
Root Barrier and Protection Mat	5kg/m^2, saturated	1.03
Substrate	3” layer, 120 pounds per cubic foot, saturated	30
Sedum, shrub, lawn	5 kg/ m^2, saturated	1.03
Total		**32.06**

Figure 16 - Additional Loadings for Alumasc-ZinCo Green Roof Assembly

Item	Description	Load (Pounds per Square Foot)
XF301 Vegetation Blanket	44 kg/m^2, saturated	9.02
Root Barrier and Protection Layer	5 kg/ m^2, saturated	1.03
Total		**10.05**

Figure 17 - Additional Loadings for Bauder Green Roof Assembly

Alumasc’s green roof assembly causes an extra burden to the roof of 32 pounds per square foot whereas Bauder’s assembly imposes only 10 additional pounds per square foot. For this rough estimate of the additional structural costs due to green roofs, an average of these two, or 21 pounds per square foot, was used. A green roof imposes an additional 21 pounds per square foot onto a roof that already weighs 115 pounds per square foot. This is about a 20% increase in weight, requiring a 20% increase in strength, and imposing a 20% increase in structural roof costs.

The next step was to determine approximately what percentage of overall building costs is attributed to support the roof structure. Ideally, we would like to have come up with a figure that states what percent of a building’s overall construction cost is typically devoted to structural members supporting the roof. This is an elusive figure, because technically, all of the structural members of the building will be affected by an increased loading on the roof. The best that can be done is to use an industry-standard assumption that about 10-15% of a typical building’s overall cost will be devoted to the entire structural system. For this study, we chose a value on the upper end of this spectrum, 14%, to be devoted to the overall structural cost.

The next step was to determine what portion of this 14% is devoted just to the roof. This becomes difficult, because for a one-story building, a very large part of that 14% supports the roof. As the building height increases, a smaller and smaller percentage of the overall structural cost is devoted to the roof. For the sake of this study, a 10-story building height was chosen. This is not an uncommon building height in urban centers. For a traditional un-greened 10-story building, it follows that about one tenth of the structural costs of the building would be devoted to the roof if the roof was designed to support the same loads as all the other floors. However, this is not generally the case. A normal roof was found to have to support approximately 115 psf. A normal floor typically must support 50 to 100 psf live load in addition to the same dead loads as the roof (substitute flooring system for roofing system). This results in approximately 160 psf for a typical lower floor. Thus, a traditional roof has to support only 70% of the loads that a lower floor would support. For a 10-story building, this amounts to 70% of one-tenth of the total structural cost of the building. We then compiled average overall square-foot costs for different types of buildings using RSMeans. Using the factors mentioned above and Equation 3-1, the increase in structural cost due to a green roof was determined per square foot of roof area. The general equation used to determine the additional structural costs due to green roof loading is shown below. The results are shown in results section 4.4.1.

$$dC = ACSF * \%S * \%R * (Wg/Wt) \qquad \textit{(Equation 3-1)}$$

where

dC = additional structural cost
ACSF= average overall cost per square foot of a typical building
%S= percentage of overall cost typically devoted to the building's structure
%R= a reduction factor to account for the fact that roof loads are generally smaller than floor loads, and
Wg/Wt = the weight of additional items due to green roof divided by the weight of traditional roofing components

Energy Cost Analysis Model

A key factor in the cost analysis for roofs in Puerto Rico is the cost of cooling energy. This is an expense that is incurred annually throughout the life of the building. Both a traditional roof and a green roof will transfer heat. It is the aim of this section to try and isolate the rate and amount of heat transferred through each roofing system in order to determine the energy costs incurred.

To determine the cooling cost savings of a green roof compared to a traditional roof we had to determine the amount of heat that enters a building through the roof. By determining the amount of heat conducted through a roof we were able to estimate the amount of energy needed to cool the building, and how much this energy will cost. To do this we tested an existing green roof located at the University of Puerto Rico at Rio Piedras. Testing on this roof was executed only after the preparation described in Section 3.1.

Our energy cost analysis model was based on measurements taken from the UPR green roof. A temperature sensing network was set up in order to collect this data, and the information was input into the heat transfer model. A discussion of the setup of the temperature sensor network is included in Section 3.2.4. The development of the heat transfer model is described below.

Heat transfer through a roof is a complex process, occurring in many different modes. In a model developed for a cost analysis of green roofs installed at Pennsylvania State University, researchers at Columbia University integrated six independent heat transfer terms. However, for a preliminary study of this nature, an analysis of the conductive heat transfer term alone is sufficient as long as close attention is given to the definition and properties of the variables used in Equation 3-2 (Personal Correspondence: Stuart Gaffin, Columbia University, 3/14/05).

Conductive heat transfer though a flat surface such as a roof is governed by Equation

3-2 (eFunda, 2005). Figure 19 shows a diagram of how this equation works.

$$Q = (k/\Delta x)\,(T_1 - T_2)A\tau$$

(Equation 3-2)

where Q = heat transferred through roof (Watt - hour)
k = thermal conductivity of the flat surface (W/m*Kelvin)
Δx = thickness of the surface (m)
T_1, T_2 = exterior and interior temperature (Kelvin)
A = surface area (square meters)
τ = time (hour)

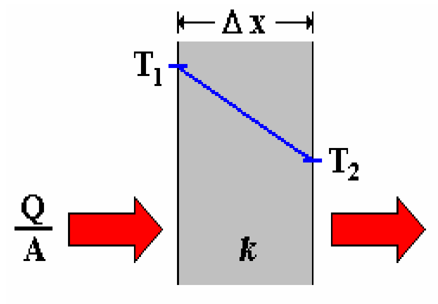


Figure 18 - Model of Conduction through a Flat Surface

This equation shows that the rate of heat transfer is directly proportional to the thermal conductivity of a given material and the difference between the temperatures on opposing sides of the insulating layer. If either the thermal conductivity or the difference in temperatures between the exterior and interior rises, the heat transferred through the roof will increase as well. The rate is inversely proportional to the thickness of the insulating layer, meaning that a thicker layer will allow less heat transfer.

Equation 3-2 describes conductive heat transfer for a uniform insulating layer. The roofs of this project, however, are composite insulating layers, meaning they are made up of different materials having different thicknesses, thermal conductivity, etc. Equation 3-2 then becomes:

$$Q/A\tau\,[\,(\Delta x_1/k_1) + (\Delta x_2/k_2) + \ldots + (\Delta x_n/k_n)] = (T_1 - T_2)$$

(Equation 3-3)

for layer 1 through layer n.

This equation told us the amount of heat transferred from the warm exterior of the building to the cooler interior, given the different material properties and the difference in temperature between the exterior and interior. It is important here to comment on what is meant by exterior and interior. As will soon be shown, the exterior is not the ambient outside temperature, and the interior temperature is not the ambient indoor temperature.

As we mentioned before, there are many modes of heat transfer occurring at both a green roof and a traditional roof. When considering heat transfer *through* the roof, conduction dominates. However, a primary mode by which the roof surface is heated is through solar radiation. Furthermore, the dissipation of stored water from a green roof involves yet another form of heat transfer that must be accounted for. In order to best approximate the heat transfer through the roof using the conduction equation described above, it was very important to carefully examine the locations chosen for the exterior and interior temperature. If this equation is to accurately model heat transfer through either roof, we must be sure that the primary means of energy transfer between the location chosen as the exterior temperature and that chosen as the interior temperature is, in fact, conduction. The choice for locations for the exterior and interior temperature requires a deeper understanding of what is going on at the surface of a vegetated roof.

We certainly could not use a location above the tips of the vegetation as the exterior temperature, because this would assume the primary means of heat transfer through the vegetative layer is conduction. However, there are other important modes of heat transfer through the vegetative layer, such as radiation, convection, and the turbulent flow of air over the roof.

Another option for the location of the exterior temperature is the interface of the vegetation and the soil or substrate layer. This seems more plausible, because there is not as much radiation, convection, or air flow through the semi-saturated soil layer. However, there is another means of heat transfer in this layer, and it is a large part of the the cooling properties of green roofs. This type of heat transfer utilizes the latent heat of vaporization of water. It is the same vehicle through which the human body's temperature is regulated. Water molecules become excited when water heats up. As they continue to heat up, some of the most excited water molecules become so excited that they undergo a phase change from liquid to gas. This endothermic reaction absorbs a high amount of energy, which is then dispersed with the water molecules into the atmosphere instead of through the roof. This mode of heat transfer can account for much of the heat transfer within the soil and vegetation layer, so it is apparent that assuming conduction as the primary means of heat transfer through the soil layer would be a mistake.

The best location for the reading of the external temperature is at the bottom of the soil or substrate layer. Below this point, the primary means of heat transfer is through conduction. This means that the composite conductive layer is essentially the layers of the traditional roof upon which the soil and vegetation were placed. We expect that the evaporation of water in the soil and vegetation layer will cause a decrease in the value used for exterior temperature, thus decreasing the difference in the interior and exterior temperature, and decreasing the overall heat transfer through the green roof as compared to the traditional roof.

Consideration must also be given to the chosen location for interior temperature. There are two apparent choices for this location, the first being ambient room temperature, and the second being the interior surface of the roof slab. The latter was chosen as the more desirable location.

The rest of the values required for the heat transfer analysis are readily available through material specifications and simple observations. We had to estimate the thickness of the structural roof slab and the other roofing materials, but this will not negatively affect the analysis, as both the traditional roof and the vegetated roof will use the same assumed values. There are many layers in a traditional roof, and many more layers in a green roof. Some of these layers do not contribute significantly to thermal insulation, due either to their ineffectiveness as an insulator, such as reflective foil, or to a very low thickness, such as a vapor retarding layer. Many of these materials do not include thermal conductivity values in their specifications, because that is not their primary use. Furthermore, there are some layers in a green roof for which it would be very difficult to determine thermal conductivity, such as the physically complex drainage layer. For this reason, in the analysis of both the green roof and the traditional roof, only three layers were used to model the boundary between the exterior and interior. These layers included the assumed structural concrete slab, the insulation layer, and the bituminous waterproofing layer. For insulation purposes, both the green roof and the traditional roof were assumed to utilize a 4" extruded polystyrene insulation layer, a 1" bituminous waterproofing layer, and a 6" structural concrete slab. It should be noted that the additional layers of a green roof - the moisture retaining mat, the drainage layer, and the soil layer - will certainly provide some conductive insulation. However, for this analysis, the thermal insulating properties of these layers will be overlooked. These assumptions will, if anything, underestimate the temperature-regulating ability of the green roof, ensuring a conservative estimate of cost savings.

Inefficiency in the air conditioning systems also had to be accounted for. The maximum efficiency for a Carnot heat pump, or air conditioner, is given by the International Energy Administration's www.heatpumpcentre.org as 0.7. This means that the air conditioner can remove 0.7 kWh of energy from a building for every 1 kWh of input energy. This assumes a "closed" system, one in which air does not enter or leave the system, and the only means of temperature increase or reduction is through energy transfer. In real life, there is ventilation of warm air out of the building and introduction of refrigerated air into the building. In the mechanical engineering field, an approximation for this phenomenon is reached through utilization of an energy-efficiency rating (EER). This is a ratio between the amount of energy removed from the building in BTU per hour and the energy consumed by the air conditioning unit in Watts. For commercial central air systems, the value of this ratio is approximately 15, that 15 BTU are removed from the building per hour for every Watt of power consumed (The HVAC Toolbox, 2005).

The final value needed for this analysis was the cost of energy in San Juan. We were able to obtain this from the publicly owned *Autoridad de Energia Electrica*, which is the sole electricity provider in Puerto Rico. Costs per kilowatt-hour were obtained for primary voltage, secondary voltage, and transmission voltage. These prices were 13.886¢, 15.561¢, and 11.363¢, respectively. Primary voltage was explained as the rate at which most large commercial buildings would receive their power, and this was the rate at which we chose to charge the energy used in our cost model.

3.3.3 Macro Analysis

Our macro analysis extended the benefits of green roofs from the individual or micro level to a larger scale. This analysis focuses on the benefits of green roofs to San Juan and its people as a whole. It would be impossible for us to conduct a thorough quantitative cost analysis in our short time in Puerto Rico, so instead we will be more qualitative, focusing on general mechanisms for savings, not specific dollar values. We will focus on several aspects of green rooftops for this analysis, including reduction of the heat island effect, reduction of runoff, and reduction of energy consumption. For the following three sections of this study, it was assumed that 20% of the land area in greater San Juan is covered by building roofs. This is an estimate based on figures for other cities such as Salt Lake City, Utah, in which it was found that roofs accounted for about 21% of the land area of that city (Akbari and Rose, 2001). Using this figure, of the 43 square miles in the San Juan Metropolitan Area, there are approximately 8.6 square miles of roofs.

Heat island Effects

From our background Section 2.2.3, it is apparent that San Juan experiences an average annual temperature that is between three and five degrees greater than outlying areas. A green roof's ability to reduce the heat island effect is one of its more unexplored facets. This is because it is difficult to arrive at a clear and definite correlation between vegetated cover in a city and temperature reduction. In our analysis, we assumed that this entire temperature increase is due to the impermeable surfaces in San Juan. We also assumed a linear relationship between area of impermeable surfaces in an urban area and increase in temperature over that of surrounding areas. This required an approximation of impermeable surfaces as a percentage of overall urban area. To do this, we used figures for urban land types from the Case Study of Salt Lake City, Utah, by Hashem Akbari and L. Shea Rose. This study used aerial photos and a computer program that analyzed pixel color to determine classification of each land type. It found that 21% of Salt Lake City was occupied by roofs, 26% by paved surfaces, and 46% by vegetation. The intrinsic assumption here is that all urban areas feature a similar distribution of land uses and relative vegetation cover, street width, and building density. From experience it is apparent that this is not the case, but we would not expect a very high deviation from the values found for Salt Lake City. For the rough nature of this analysis, the Salt Lake City numbers should suffice. A more in-depth study could make use of GIS software or aerial photography to obtain figures specific to San Juan.

We determined how much of San Juan's impermeable area is covered by one, two, five, and ten percent implementation of green roofs over traditional roofs. We then found corresponding percent coverage of impermeable space by new green surfaces for each case. We then determined the corresponding average temperature decrease for each case by assuming a linear relationship between impermeable space and temperature increase.

Runoff Effects

This analysis was similar to the analysis of the heat-island effect in that it combined data from other studies and applied this data to local conditions in San Juan. In a study conducted in Philadelphia, PA by Charlie Miller of Roofscapes, Inc., a green roof's water retention and subsequent runoff was tested for rainfall patterns in Pennsylvania. It was found that 90% of precipitation in Philadelphia was produced by frequent, short and intense storms not generating more than 2 inches of rainfall in a 24 hour period. In a 9 month test run on the roofs with actual and simulated storms, it was found that the roof generated only 15.5 inches of runoff despite 44 inches of rainfall. This means it either retained or dispersed 65% of the rainfall. The highest intensity storm generated 0.4 inches of rainfall in a 20 minute period. This occurred after a period of extended rainfall in which the roof was already saturated. Figure 16 shows the rainfall and runoff recorded during this event. For minutes 30-49, the total rainfall was 0.4 inches and the runoff was 0.17 inches. Even for a severe rainfall event on an already saturated roof, 57% of the runoff was attenuated. From this data, it seems that it is reasonable to assume that runoff can be curbed by about 60% as long as the roof and rainfall in our study are similar to those in the Philadelphia study.

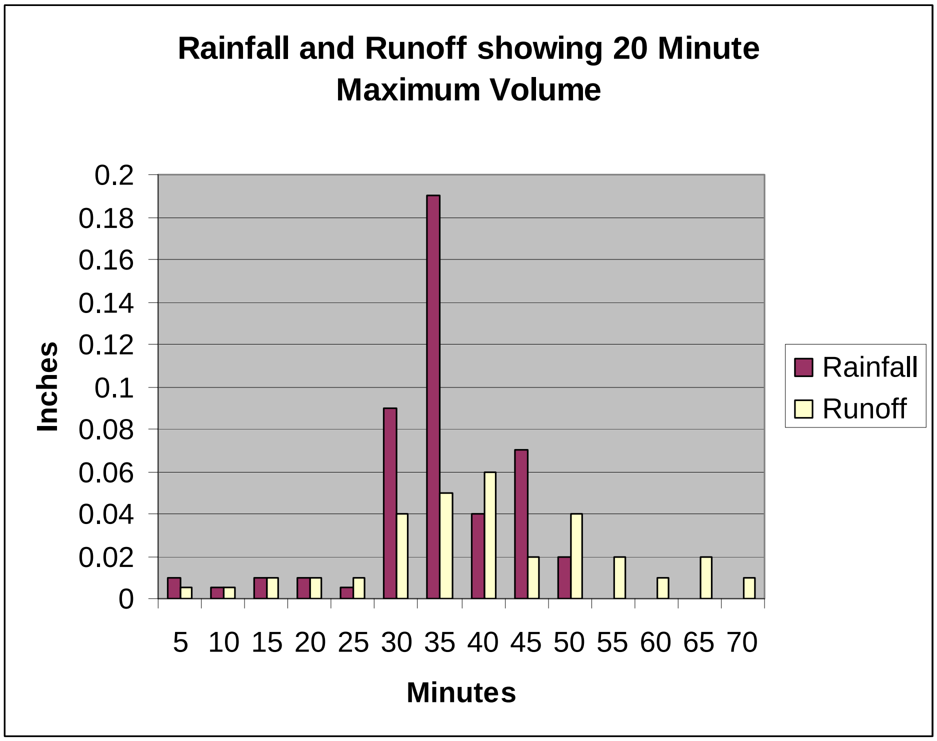


Figure 19 - Rainfall and Runoff: 20-Minute Maximum Volume in 9-Month Study (Miller, 1998)

The next step was to compare the parameters and results of this study to the attributes of the green roof system proposed by our study and to rainfall patterns in San Juan.

The green roof used in the Philadelphia study was a 2.74" thick extensive green roof with all the components used in our proposed green roof. Our proposed extensive roof is approximately 4.5" thick, so it is reasonable to assume similar performance of our green roof if it were subjected to Philadelphia rainfall patterns.

However, rainfall in San Juan is quite different from rainfall in Philadelphia. Rainfall in San Juan was characterized using 1996 data from the National Oceanic and Atmospheric Administration. Three months were chosen, characterizing light rainfall (December), moderate rainfall (August), and heavy rainfall (September). Monthly rainfall in 1996 is given in Figure 17.

Month	**Rainfall**
January	5.74
February	2.44
March	2.06
April	5.04
May	0.28
June	0
July	6.74
August	6.07
September	15.69
October	2.36
November	7.54
December	2.96
Total	**56.92**

Figure 20 - 1996 Monthly Rainfall in San Juan (National Oceanic and Atmospheric Administration)

As can be seen from Figure 17, September had significantly higher rainfall than any other month. This is due to the effects of Hurricane Hortense in that year, causing rainfall levels in September to climb to double annual averages for that month. Five months had rainfall comparable to that of August, and the remaining five months had rainfall less than that of December. Hourly rainfall records for August, September, and December of 1996 are given in Appendix J. We then determined how much of the total rainfall occurred in events totaling less than 2" in a 24 hour period by examining the three sample months for which we had data, and applying the results of those to the rainfall of "similar" months, as described above. The results were then compared to the Philadelphia study to determine to what percentage of rainfall we could expect green roofs in Puerto Rico to attenuate. These results were then multiplied by the percentage of roof area in San Juan to determine the overall effects to aggregate runoff in San Juan, and thus the reduced strain in infrastructure stress.

Energy consumption

For analysis of overall reduction in energy consumption due to the implementation of green roofs, we extended data from our micro cost analysis to a larger scale. We determined how much energy could be saved in San Juan as a function of percentage of total roof area in San Juan that could be vegetated. This analysis was more straightforward than the other two aspects of the macro analysis because it is directly tied to the extensive study completed in the micro cost analysis. In that analysis, it was found that energy transferred through traditional roofs in Puerto Rico result in costs of approximately $0.54 per square foot whereas that for green roofs results in only $0.23 per square foot, representing a 57% savings in the cost of energy transferred through the roof. These figures were scaled to one, two, five, and ten percent implementation over all existing roofs in San Juan in order to show the energy and cost savings for each level of green roof use.

We then determined what percentage of the cooling load of air conditioning systems in San Juan was due to heat transfer through the roof as opposed to other sources, such as exterior walls, doors, windows, and internal heating. After that, we determined the total energy expenditure for buildings in San Juan, and determined what percentage of that was due to cooling costs. Using the figures for total percentage of energy costs represented by cooling costs and total percentage of cooling costs represented by heat transfer through the roof, we were able to conceptualize a percentage of total energy savings due to certain levels of implementation of green roofs in San Juan.

3.4 Promoting Green Roofs in Puerto Rico

A preliminary study by our liaison, Dr. Ángel David Cruz, suggests promising results for support for green roofs in Puerto Rico. This survey analyzed the marketing potential of green roofs for single unit houses, and the results showed that approximately 75% of those surveyed were interested in this technology. These figures alone show a great indication of market capabilities just in residential areas, but do not address the interest or support of larger businesses or the government.

For this project, we identified three groups to whom we would focus a marketing strategy. These groups included potential commercial customers, potential builders and industry insiders, and environmental organizations that may have interests in promoting the installation of green roofs. We obtained contacts within these groups by networking with various individuals in Puerto Rico who were located either directly through Dr. Cruz and Ms. Beatriz Arsuaga, or through contacts provided by them.

We then developed separate marketing strategies for each of the three groups. These are included in the next few sections along with a sampling of the questions that could be posed to the different groups. These questions were pre-planned, and used as a guide for our meetings, not as a mechanical interview. Each individual contact warrants a specialized set of questions. These questions seek to increase the knowledge of green roofs among people who can have an influence in the green roof industry in Puerto Rico, and also to increase our own knowledge of the strengths and weaknesses of green roofs and the perception of green roofs in Puerto Rico. The results of implementation of these marketing strategies are given in the results section.

Our predictions of what we will be looking at for interest from the separate entities are as follows:

- The potential buyer and corporations are going to be most interested in cost effects, with the benefits of life cycle cost being greater in savings than that of a traditional cement roof used in Puerto Rico today.
- The EPA and federal agencies will be interested in feasibility of these green roofs including runoff effects, reduction in energy use, and reduction in alteration of local climate.
- Construction, engineering, and architecture firms will be interested in the potential industry and any government incentives designed to foster the market.

3.4.1 Investigating the Interest and Needs of Potential Customers

We established several reasons that our commercial customers in San Juan may be interested in purchasing a green roof. These included the economic benefits due to energy savings, the aesthetic appeal, and the public image benefits associated with installation of environmentally friendly green roofs. We also had to anticipate the reservations that the customer may have in investing such a considerable amount of capital in a green roof, when a traditional roof can be installed for far less. We developed the following interview strategy to convey the key benefits of green roofs to potential customers.

- Presentation of results of our life-cycle cost analysis model in order to demonstrate the long term savings associated with installing a green roof. The life-cycle cost analysis should be presented in order to justify the high installation cost of green roofs with the future energy and maintenance savings.
- Presentation of the aesthetic and public image benefits of installing green roofs. Aesthetic benefits can be shown through the use of photographs and details of successful green roof projects elsewhere. Public image benefits can be shown through articles and praise for companies that have installed green roofs elsewhere. Displaying an environmentally friendly attitude can be very beneficial to companies in Puerto Rico, and installation or support of a green roof is a cost effective way for companies to portray themselves this way.
- Demonstration of the types of incentive programs that have been used in other countries to encourage installation of green roofs.

These main points should be covered in conjunction with the following questions in order to open a dialogue between ourselves and our customers so that knowledge about green roofs and the environment for green roofs in San Juan is passed both ways.

- What knowledge did you have of green roofs before your contact with us?
- Where did this knowledge come from?
- Of the advantages we have shown you, which would be the most influential in your decision as to whether or not to install a green roof?
- Beyond the initial high cost of green roofs, what other reservations would you have with investing in a green roof?
- How do you feel about the time-frame over which a green roof "pays for itself?"
- What payback period would make green roofs a viable option for your firm?
- What other information would you like to see from current or future studies of this technology?

3.4.2 Investigating the Interests and Needs of Environmental Organizations

Another group that is integral to the implementation of a green roof industry in San Juan is environmental organizations. These organizations can help to disseminate information and lobby the government for incentives and support. Whereas we determined the main interest of potential customers to be their individual benefit from green roofs, we theorized that environmental groups would be more interested in how green roofs promote the common good and how they benefit the environment. These benefits are outlined in the macro analysis of green roofs, and include a reduction in overall energy consumption, attenuation of runoff, and mitigation of the urban heat-island effect. Other areas of interest include municipal beautification. The interview strategy for conveying these key points is as follows.

- Demonstrate results of macro analysis of green roofs showing overall benefits provided as a function of percent implementation of green roofs in San Juan.

- Present renderings of how San Juan could look given certain levels of implementation of green roofs.
- Present ways in which other countries have encouraged the use of green roofs, including incentive programs and legislation, in order to convey the types of programs they could pursue.

After presentation of these main points, a two-way discussion should be initiated and guided by the questions below.

- What knowledge did you have of green roofs before your contact with us?
- Where did this knowledge come from?
- Have you had any involvement with promoting green roofs or any other energy efficient construction methods?
- What would you see as the primary barriers to implementation of this technology?
- Have you found that a lot of people or companies are willing to invest in environmentally friendly construction or practices?
- What types of funding or grants are available for further research in this type of technology?
- How willing would the government be to provide incentive programs similar to those we presented today?

3.4.3 Investigating the Interests and Needs in Industries Related to the Construction of Green Roofs

Industries relating to the construction of green roofs include those involved in the supply, design, and construction of these roofs. A key interest of these groups is the possibility of a new market with innovative technologies. They also may have an interest in the technical side of green roofs, including what products are used, how they are constructed, and what the itemized costs are. In order to convey this information, the following interview strategy was developed.

- Presentation of a background of green roofs and their benefits with an emphasis on the technical aspects of green roofs. Information on products, construction methods, and pricing should be presented. This information can be found in Appendix G.
- Presentation of company profiles for companies that specialize in green roofs (e.g. Alumasc, Bauder, HydroTech USA) in order to show the entrepreneurial opportunities in this industry.

The following questions were developed to guide an interview with this sector.

- What knowledge did you have of green roofs before your contact with us?
- Where did this knowledge come from?
- What do you see as the main things that would stop your clients from requesting or pursuing green roof technology?
- Do you feel that a lot of your clients are concerned with the environment?
- Are your clients geared towards the short- or long-term for their construction

projects?
- How long do you think your customers would be willing to “wait” for a payback period?
- Would you be willing to suggest the installation of green roofs to your clients?
- What other information would you need in order to pursue this technology.

4 Results, Analysis and Recommendations

The results section is broken down into seven different areas. The first and second sections outline the results of our analysis and rehabilitation of the existing green roof at UPR. The third section deals with the different materials and plants that we have found and would advise for long term use on green roofs in Puerto Rico. The fourth section shows the findings from our life-cycle cost analysis of green roofs and traditional roofs. It also analyzes the impacts that green roofs could have on society and the environment. The fifth section discusses the results of the development of the temperature sensor network. The sixth section outlines the lessons learned from our interviews with businesses in Puerto Rico, and the final section provides recommendations for future work towards our main goal of implementing a green roof industry in Puerto Rico.

4.1 Analysis of the Original Roof

Figure 21 - Investigation Chart of Original Roof

Figure 21 shows how the original roof has been broken down into sections based on the results of investigating plants, materials, and the success of each section constructed on the original rooftop. Identification of which sections still flourished was a process necessary in order to learn from the evolution of the green roof from direct observation of plants, physical analysis of sections, and review of original roof design documents. Physically sorting through the rooftop sections and different layers in comparison with the information on the original construction has led to several conclusions concerning the varying conditions of materials and plants on the roof. Upon initial investigation and deconstruction of the roof, we observed three major differences in variations of the standard green rooftop layer along with other evidence of why the roof had failed.

- The roof was originally planted with *Kalanchoe*
- The original substrate was a volcanic rock varying in depth from 4 cm to 10 cm
- The roof's condition showed a complete lack of maintenance leading to an over growing of the original *Kalanchoe*.
- Grasses had taken over most of the roof dying in recent months due to lack of rainfall
- The most successful section consisted of using a water retention layer and standard green roof sections, shown in the water retention sections in Figure 21.
- The second best section was the standard traditional green roof having sparser growing plants in the moderate and little growth sections in Figure 21.
- The last section, the no growth section in Figure 21, had no vegetation left on it. Its layers consisted of the drainage layer, a larger substrate layer separated from a smaller substrate layer by a cloth layer.
- Small variations included variations in the substrate's gradient and spacing of plants from 10 cm to 15 cm to 20 cm apart. (These small variations did not seem to have much influence on the success or failure of the vegetation. It was the sections layers that were either a success or a failure.)

Our findings concluded that a water retention layer is necessary for green rooftops in Puerto Rico. Due to possible extreme drought conditions, water needs to be retained and released slowly for plants to survive. The water retention system on the roof at UPR was inadequate for water retention demands in San Juan. Although it is possible to obtain drought-resistant plants, every plant has some limit, and it appears that the drought experienced in March in Puerto Rico surpassed the limits of many of the plants on UPR's green roof.

Also, *Kalanchoe* by itself was an unsuccessful choice for green roofs due to its inability to spread. Other findings were the side with more vegetation growth in the green section was most likely due to its proximity to two larger trees next to the roof. Grass seeds and seeds from the nearby trees were carried to the roof by the wind, producing undesirable plants on the roof. An extensive roof is not meant to support the growth of trees whose deep-growing roots could damage the roof layers.

4.2 Rehabilitation of Existing Green Roof at UPR

At the end of the fifth week after watering steadily each morning and the use of fertilizers, the test plot showed significant new growth. By the end of the sixth week, it looked like a healthy, well watered field shown in Figure 22. This was due to our watering and seeding efforts and some cooperation from the weather. Many lessons were learned from the rehabilitation of this roof. The first was that green roofs may not be maintenance free. If someone had taken a little time to take care of this roof each year, the spread of drought-vulnerable grass may have been stopped.

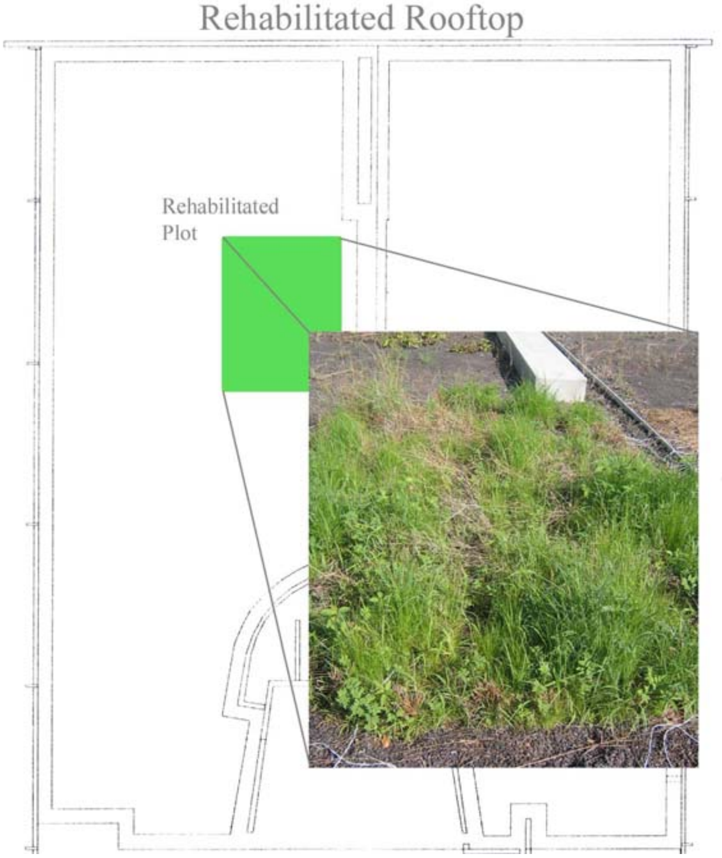


Figure 22 - Rehabilitated Rooftop

4.3 Assessment of Substrate Materials and Plants for Use in San Juan

4.3.1 Assessment of Locally Available Plant Species

In the seven weeks that we were in Puerto Rico we did not have enough time to determine which plants actually worked. That will have to be determined with research afterwards. The reason for this was that the plants may live while we take care of them and watch over them, but as soon as we leave and they begin to live without our nurturing they may die immediately. If this happens the plants are a failure. What we did do while we were there was to determine what plants native to Puerto Rico have a good chance of success.

Through speaking with plant specialists, botanists, nurseries, and green rooftop companies we have compiled a list of 20 different plant species that we could try, found in the Figure 23. When choosing these plants we first looked at how they could stand up to a drought or heavy rainfall, since these are both aspects of the Puerto Rican climate. Being atop of a roof, the plants had to be able to handle direct sunlight as well as direct rainfall and more direct winds.

Plant Characteristics

Plant Species	Water needs	Sun	Height	Width	Reproduce	Suitability for Green Roofs
Sphagneticola trilobata	Light watering	Full sun	6-12"	18-48"	Cuttings	Good match
Maleophora luteola	Light watering	Full sun	NA	4'	NA	Good match
Maleophora crocea	Light watering	Full sun	7"	NA	Cuttings	Good match
Ipomoea pes caprae	very light watering	Full sun	3-5"	100'	Viney	Good match
Delosperma cooperi	Light watering	Full sun	6"	18"	NA	Good match
Delosperma nubigenum	Light watering	Full sun	3”	10"	NA	Good match
Crassula muscosa	very light watering	Full sun	6-12"	6-8'	Cuttings	Good match
Aloe vera	Very light watering	Full sun	NA	8”	Offsets	Does not spread well
Aloe walmsley's Bronze	Very light watering	Full sun	NA	6"	Offsets	Does not spread well
Cactaceas	Very light watering	Full sun	NA	NA	NA	Does not spread well
Kalanchoe	Very light watering	Full Sun	18"	NA	Seeds	Does not spread well
Sedum mexicanum	Light watering	Full to partial shade	6"	spreads slowly	Seeds	Does not spread well
Sedum diffusum	Light watering	Full sun to partial shade	1"	spreads slowly	NA	Does not spread well
Delosperma kelaidis	Average watering	Full sun	2"	12"	NA	Too much watering
Haworthia limifolia	Average watering	Partial shade	6"	6"	Seeds or Cuttings	Water and Sun problems
Haworthia margaritifera	Average watering	Partial shade	6"	4¨	NA	Water and Sun problems
Haworthia paradoxa	Average watering	Partial shade	NA	NA	NA	Water and Sun problems
Bougainvillea	Light watering	Full sun	8-10'	6-8'	Cuttings	Better for intensive rooftops
Carissa	Average watering	Partial to Full sun	6-10’	NA	NA	Better for intensive rooftops

Figure 23 - Table of Suggested Plants

We were not able to try all of these plants due to a lack of funds and available plants at local nurseries. These plants are all very drought resistant as well as able to handle the climate of Puerto Rico. It has yet to be seen whether these plants can handle the direct sunlight and other unique effects from on top of a roof.

Although each of these plants have some of the same qualities, they are each unique in their own way. There were many plants which we researched but could not purchase to test on the roof. Figure 23 shows possible plants and their different qualities. The table is structured from the top down from the best alternatives to the worst. Here you can see the seven plants which we recommend testing to assess suitability for an extensive low maintenance green roof top in Puerto Rico. Other plants could live atop a roof, but other climates may be better for them. Others need more maintenance in terms of watering unless there can be an irrigation put in place.

We looked into 6 different nurseries in the San Juan area. Of these nurseries, which are mentioned in Appendix C, some did not carry any of the plants we were interested in, while others carried most of them. In the table it shows which plants are carried at which nursery.

4.3.2 Assessment of Substrate and Soil Materials

Limitations on the depths of soil and substrate are needed for minimal loading capacities. We are looking at depths that are not going to present a bearing problem in the structural loading, but are deep enough to provide a growing medium. Through research of other green roofs and contacts with several experts including Dr. Muñoz, a professor in soil chemistry and mineralogy research, at the University of Puerto Rico we have possible layers presented below with specific properties to maximize growing results.

Our selected soil layers consist of two soils, a topsoil called Metro-Mix 400 and a natural soil provided by Professor Muñoz. Several properties that these soils should have are listed below.

- Provide support to the plants
- Retain sufficient humidity
- Porous to provide air to the system
- Light in its density
- sufficient organic matter to retain nutrients

The first soil is store bought topsoil called Metro-Mix 400 which has high capabilities of water retention and good air porosity. For our experiment, this is the soil used in each of the plots found on the roof in the Past Experimental Plot section of Figure 21. The second soil used is soil suggested by Professor Munoz. It is a high clay concentrate, which can hold up to one hundred times its weight in water. Silt and peat moss will be incorporated in the soil. These will provide nutrients to help the growing process along with helping aeration; however the levels of silt will have to be watched closely, because too much will end up sealing off the pores. This soil will be used in a second experiment on the roof apart from the experimental plots, denoted by the Future Experimental Plots section in Figure 24. This will be an alternative growing experiment, explained in greater depth in the section below, Setup-Tests of Alternative Soils.

Substrates for green rooftops need similar properties to soils. Listed below are these properties.

- Need to be porous
- Light in weight
- Particle sizes appropriate for the shallow depth

Using these standards we established three different options of substrate and decided to test two due to their availability on the island. The original substrate material used on the rooftop was volcanic rock. It is a light substrate and very porous, able to retain large amounts of water, and provides aeration to the roots. Limestone, our second option, is found across the island and is a plentiful element to use on roofs. It is porous like the volcanic rock but it is a little denser. However, its color provides an interesting aspect that we hope will help the roof. Unlike the volcanic rock, which is black, the limestone is white and will reflect more sunlight, keeping the roof and soil cooler. Our last option, which we are not attempting to use due to its unavailability on the island, is crushed brick. Crushed brick is used widely across the United States but is not very widely used across the island, as most houses are created with cement instead. Like the other materials, this is porous and a good median for growing, so we still recommend it where available on the island of Puerto Rico.

Selection of these substrates and soils was due to our extensive investigation of substrate materials through many contacts with experts in soil, horticulture and companies in the green rooftop market. A list of our contacts is in Appendix A.

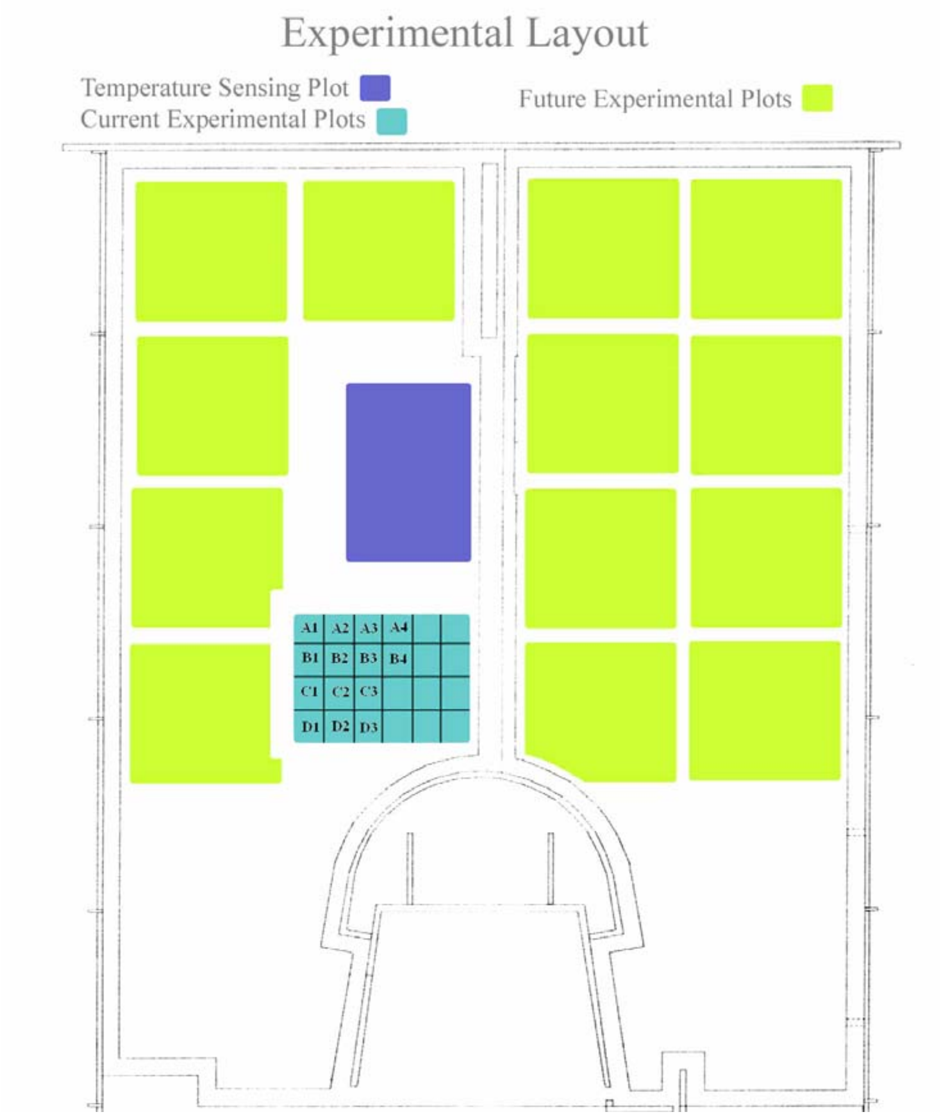


Figure 24 - Experimental Plot and Possible Future Plots

4.3.3 Experimental Test of Substrates and Plant Species

The set up of our experiment is based around the testing of two substrates and a variety of drought resistant plants over an extended period of time. This experiment will be initiated and established by our group and then continued according to our guidelines by other individuals, recording observational information that we have recommended. Recording the expansion of the plants along with their ability to sustain drought conditions in the different substrates will be the main observations.

Experimental Plots

The plots have dimensions of seventy centimeters by fifty-four centimeters. Within the plots there are eight different plant species, in sixteen different plots. The basis of what we intend to do is a simple variation in the substrate between two growing plants of the same starting size. The first substrate, volcanic rock, is a widely used substrate in the green roof industry and the second, limestone, is a porous substrate plentiful on the island of Puerto Rico. Two plants of each plant species were obtained and were placed in the middle of the plot. For each species, one plant was rooted in limestone and the other in volcanic rock. The plants vary from several different kalanchoes to grasses to more woody plants like the allamandas as shown by the Past Experimental Plots section in Figure 24 and the specific names in Figure 26.

The substrates and soil layers are based upon the standards stated before of weight and minimal depth. The depths of these two are essentially due to their need to be anchored from forces like; rain, wind or any other conditions of torque against the roots. The recommended depths therefore are between 5 and 15 centimeters for an extensive roof. As shown in Figure 25, the substrate depths of volcanic rock and limestone have a variation of 4 to 6 centimeters and soil depths of approximately 1 to 2 centimeters deep.

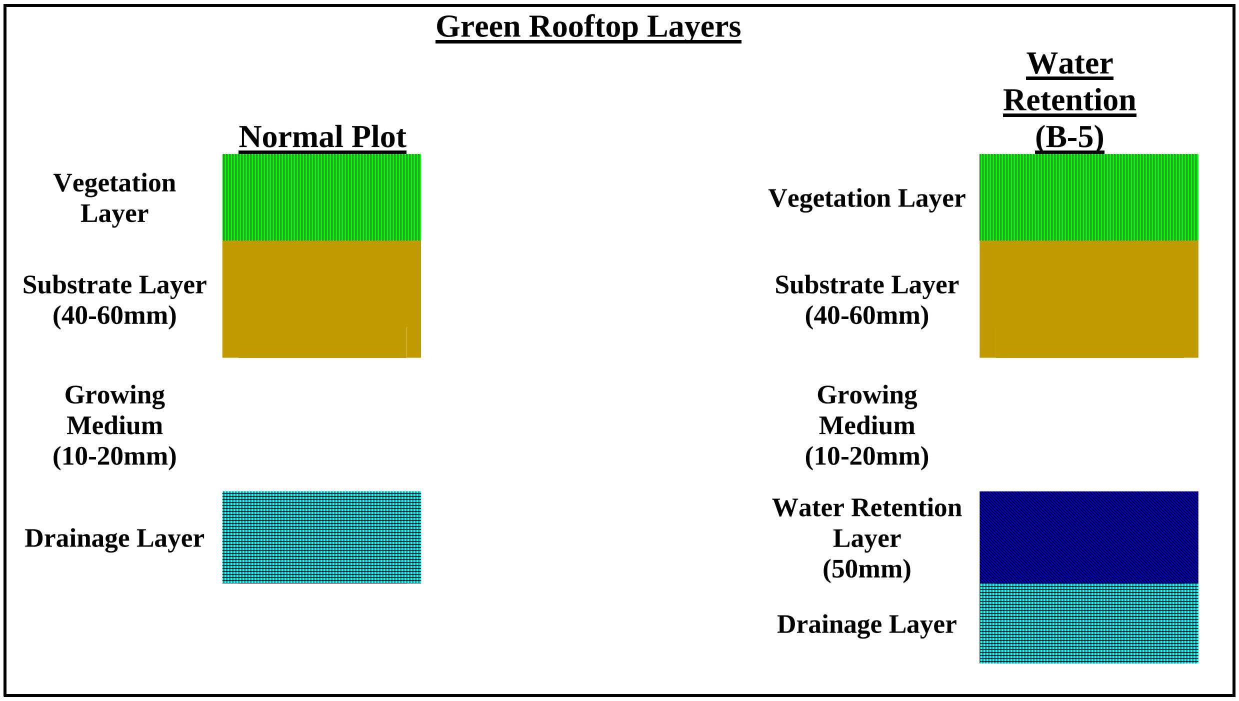


Figure 25 - Soil Layers Present in Experimental Plots

The last variation that we have incorporated into our test is a water retention layer in one of the experimental plots. This water retention layer (found in storage shed on green roof at UPR) was one of the original materials used on the roof; it was very successful in all of the plots with which it was used. Using the same plants from A-4 and B-4 in Figure 26, we constructed a plot in B-5 which uses the layer. These plants are in the same family as cactus plants and required water more slowly over a longer period of time. The slow release of water from this layer will be very comparable to the needs of the plant. The retention layer is the only variable in this plot, as the layer of soil and substrate are the same as all of the other plots.

Experimental Plots

6	Open for Future Development	Open for Future Development	Open for Future Development	Open for Future Development
5	Open for Future Development	*Haworthia limifolia* T.B.D. T.B.D.	Open for Future Development	Open for Future Development
4	*Haworthia limifolia* T.B.D. T.B.D.	*Haworthia limifolia* T.B.D. T.B.D.	Open for Future Development	Open for Future Development
3	T.B.D.	T.B.D.	*Allamanda catharica*	*Allamanda catharica*
2	*Kalanchoe blossfeldiana*	*Kalanchoe blossfeldiana*	T.B.D.	T.B.D.
1	T.B.D.	T.B.D.	*Kalanchoe*	*Kalanchoe*
	A	B	C	D

Figure 26 - Plant Names in Experimental Plots (T.B.D-To be determined)

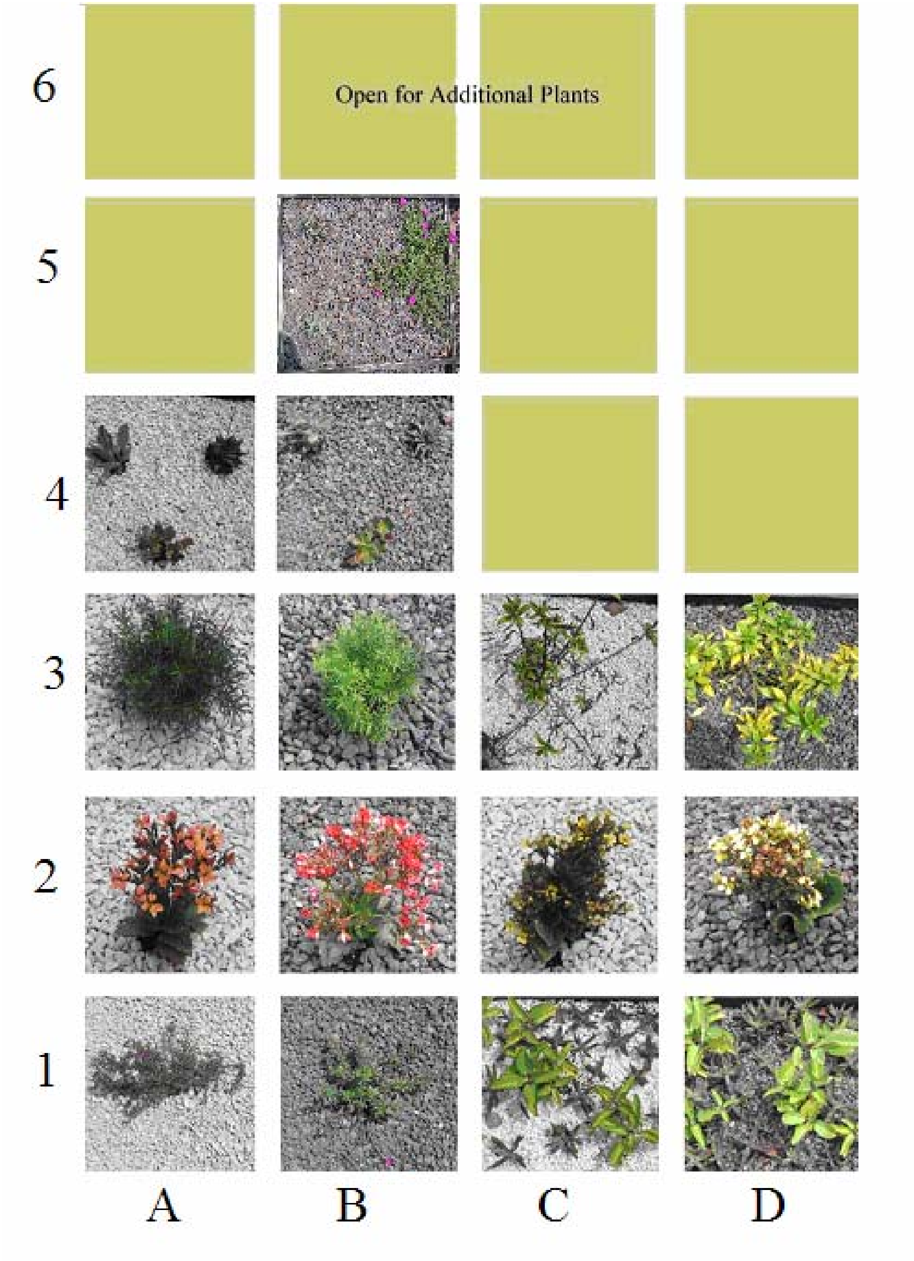


Figure 27 – Plants Pictures in Experimental Plots

Tests of Alternative Soils

The second part of our experiment is planted on a larger section of the roof using the alternative natural soil, mentioned in section 4.3.2, outside of the experimental plots. Currently we have two plants, the *Carissa* and grape vines, which are themselves larger and will expand and grow on a scale that will have the space needed on the other parts of the roof. Here they will need less maintenance and there will be minimal worry about overtaking of other plants. The soil depth will have to change due to compensate the larger plants, matching that of the substrate layer of 4 to 6 centimeters deep.

Long Term Monitoring Protocol

This experiment is strictly observational with very minimal interference to achieve the most realistic results of a natural green roof as possible. In order to achieve this, recommended monitoring and data collection protocol for researchers following up our work here is attached in Appendix D. The guide is self explanatory, and is to be conducted on a bi-weekly schedule. Every two weeks the individual will measure the plant's growth and observe and record the condition of the plants. For measurements of radial dimensions, the expected distances will be a maximum width of the plants ground coverage going in each direction vertical and horizontal to the plot box. Leaves and flowers will be measured across the face of the item for its diameter. Height will be the tallest vertical point on the plant. These measurements will be followed by the general observations in the comments section of the observational guide, looking for browning of any parts of the plants or unusual behaviors.

Problems that might occur are the overgrowth of plants which may spread into other plots. This is a very possible occurrence, and if the plants are crowding the edges of the box then a simple trimming and transplanting will have to take place. These transplants can be moved to anywhere on the roof that is open. Watering will be another condition that is questionable. Realistic rainfall conditions are wanted, but during extreme drought nothing can survive as we experienced on the original green roof. After extended periods of no rainfall, the plants should be watered. Simply spraying the plots for a few minutes with a hose and tap water should be sufficient.

Preliminary Observational Findings

At the end of our project, there were already observable differences between the results of each plant in the limestone compared to the same plants in the volcanic rock. In Figure 23 there is a complete list of all plant characteristics in the first observational study. From our plots limestone seems to have effects on plants in a negative manner in several plots and might not be a good option for green roofs. Certain plants such as the Allamanda looked healthy when planted in the volcanic rock with few leaves falling off, but looking next to it in the limestone plot it had lost most of its leaves and produced fewer flowers. The plant in plot B1 has grown very well in the volcanic rock, expanding out already to touch the edges of the plot. This plant will need to be transplanted soon. The same plant planted next to this in plot A1 has expanded but not as rapidly. It has several brown leaves toward the center and shows signs of being less healthy. Although this happened in the limestone some problems that could have had an affect on the plants were the pH balance and a possible lack of nutrients in the limestone. This should be studied for a longer period of time to better determine what the problem is and see if options are available to reduce these problems.

We were able to see that there were a few plants that did not turn out well. Due to the small amount of plants that we were able to put into our plot even though they did not work in our plot, we still give it a chance. The *Haworthia limifolia* was planted in three different plots but did not thrive in any of them. The ends of its stems are turning brown and it does not have a healthy look. It spreads very slowly so we could not determine if it has grown much.

Recommendations of Future Experiments

Determining who will continue our research after we leave is an integral part of our project even though it takes place after we have left. Without someone leading another project, our work will have little lasting purpose. We have received help from Professor Ángel David Cruz Baez, as well as people in the biology department at the University of Puerto Rico. These people are all interested and we have contacted them about getting more people involved and knowledgeable about green roofs as well as having them continue our project. They could possibly talk to students who are in the area year round, so they can be taking measurements and working on the roof all year round. With more time and money they could have a more in-depth understanding of what plants actually work in all conditions. To combat the problem of not having enough money, whoever is the head of the next project should go directly to powerful people that would be interested. The head of the University of Puerto Rico could be interested as well as a government official who has been known to support environmental activities.

If all goes well and there is someone who will follow our lead on a larger green roof project there are several open plots that could be used in the future. The Future Experimental Plots section shown in Figure 24 is an example of how it could be set up. Due to lack of funding our project was forced to be very minimal in aspects of experimenting on an entire roof. The person continuing our research after we have left Puerto Rico will hopefully have a budget that will be able to fund the completion of several ideas that we either did not have enough time to look into or lacked the money to complete. Listed below are our ideas with explanations

In Figure 23 we have compiled a list of plants that are possibilities for the roof. Research should be continued with the suggested plants to determine which of these plants will work the best along with results from our experimental plots seeing how well each plant survived and in which soil it thrived. After deciding which plants are best out of a comparison, set up of the roof with more plants in much larger plots can be continued.

The original roof was set up in plots which can be used to keep separation of the plants from overtaking each other, insuring that no one plant gets in the way of another plant's survival. The rooftop is very expansive and provides many areas for growth. Several plants should be tested along with plots that have combinations of plants; some that spread for ground cover and some that are resilient to heat. For soil and substrate, the current roof should be deconstructed down to the drainage layer. On top of the drainage layer after the area is cleaned you can rebuild the growing medium creating any variations that you would like to experiment with. After all the plots are created, regular documentation of the progress should be kept. However more in-depth observations should be kept to really extend past the progress that we have made. PH levels, moisture content, organic percentage, nitrogen levels, density and nutrients in the soil could all be monitored to show exact specifications for growing media which are most successful and when fertilizer and maintenance is needed. This process can be helped by Professor Muńoz at the UPR experimental station who has soil on storage for green rooftop usage. He is very helpful and can help with the chemistry make up of the soil.

Two other side notes that could be tied to this larger experiment are runoff and possible irrigation systems. Runoff could be tested large scale to get actual numbers, by figuring out a system of water meters on all of the drainage pipes going off of the roof. After a storm you would have the data of rainfall and the contrasting information on how much runoff came out of the pipes. This would give more exact values to present to other individuals for city planning to help the storm water crisis.

Irrigation systems could also be looked into further. Options for a possible leaky pipe irrigation system were already looked into, it is a simple system easily created with a water source. Our ideas for a water source would be to create a water basin for catching rain water. Elevating this above the roof you would then have gravity to work for you to power the irrigation system. With a simple valve attached close to the ground green roofs would have access to water through the dry seasons, still very minimal maintenance but also control to help the plants not fade away during this time.

4.4 Temperature Sensing Network

After much delay due to the University of Puerto Rico strike we were finally able to setup and test the temperature network on the roofs. We completed several days of data gathering to use in our micro cost model. As a result of setting up and using the network we were able to gain a greater understanding of its accuracy, ease of use, and data gathering abilities.

4.4.1 Accuracy

Originally there was some concern about the accuracy of the entire temperature network. Issues such as the step size of the Analog to Digital converter and the resistance in the lead wires were the major concerns. However after performing some simple checks it was found that these issues did not play as large of a role as originally expected. Our best error evaluation puts the accuracy of the entire system at about, which we consider to be reasonable for our limited budget and the intended use of the network.

4.4.2 Implementation

The temperature sensor network has undergone many important changes over the course of seven weeks. These changes not only made the network more robust, but also facilitated its use by an inexperienced user. Things such as the pen body probes and the protective project box enclosing the important wiring connections should allow the network to endure any adverse conditions it may encounter over the coming years. The simplified wiring, reworked program, and the user's guide included in Appendix E of this report will help the future users to gather and manipulate the data they desire from the temperature network effectively.

4.4.3 Data Gathering

The temperature sensor network had two main purposes, first to gather the temperature data we needed for the micro cost analysis, and second to provide people interested in the roof with an array of temperature data. To satisfy the first goal, the sensors were split into two groups and measurements were taken on the green roof, and the traditional roof. Everything ran quite smoothly after a few minor adjustments and we were able to get the data we wanted from the network. We then manipulated this data in excel to find hourly averages and maximum and minimum temperatures for each roof, shown below in Figure 28, which was used in the micro cost model.

Traditional Roof

	4/21/2005	
		max
11:20 to 12	122.7	140.9
12 to 1 PM	98.6	
1 to 2	78.0	**min**
2 to 3	85.3	73.4
3 to 4	80.2	
4 to 5	75.8	

	4/22/2005	
10:45 to 11	132.7	**max**
11 to 12	134.2	145.9
12 to 1 PM	131.6	
1 to 2	140.2	**min**
2 to 3	126.2	113.4

	4/25/2005	
10:15 to 11	123.6	**max**
11 to 12	125.6	133.4
12 to 1 PM	122.2	
1 to 2	97.4	**min**
2 to 3	93.6	79.3
3 to 4	102.0	
4 to 5	104.4	
5 to 6	97.3	
6 to 7	89.4	
7 to 8	88.9	
8 to 9	88.5	
9 to 10	88.5	
10 to 11	87.5	
11 to 12	85.9	
12 to 1 AM	85.8	
1 to 2	85.3	
2 to 3	84.0	
3 to 4	83.0	
4 to 5	80.8	
5 to 6	80.2	
6 to 7	80.8	
7 to 8	84.2	
8 to 9	91.7	
9 to 10	90.3	
10 to 11	94.1	

Green Roof

	4/21/2005	
10 to 11	82.9	**max**
11 to 12	85.9	102.4
12 to 1 PM	86.7	
1 to 2	81.7	**min**
2 to 3	79.8	76.9
3 to 4	81.0	
4 to 5	78.7	

	4/22/2005	
10:30 to 11	83.5	**max**
11 to 12	86.3	93.1
12 to 1 PM	89.7	
1 to 2	91.4	**min**
2 to 3	92.7	82.7

	4/25/2005	
10:40 to 11	86.7	**max**
11 to 12	88.9	92.4
12 to 1 PM	91.2	
1 to 2	88.2	**min**
2 to 3	80.1	78.9
3 to 4	82.9	
4 to 5	84.8	
5 to 6	85.5	
6 to 7	85.4	
7 to 8	85.0	
8 to 9	84.5	
9 to 10	84.2	
10 to 11	84.0	
11 to 12	83.7	
12 to 1 AM	83.4	
1 to 2	83.2	
2 to 3	83.1	
3 to 4	82.9	
4 to 5	82.6	
5 to 6	82.4	
6 to 7	82.3	
7 to 8	82.4	
8 to 9	83.0	
9 to 10	84.0	
10 to 11	85.5	

Figure 28 – Traditional Vs. Green Rooftop Daily Temperature Readings

The second goal of having a more permanent temperature sensor array to measure temperatures on the roof was of more importance to our sponsor. Moving all the sensors to the green roof and running the wires to different sections of the roof was rather simple, but deciding where to locate the computer required for the network was somewhat more difficult. Our liaison wanted the computer to be located inside the office from which we had worked; however this would require that we run longer wires from the roof inside to the building. We decided that with the time we had remaining due to the strike holdup that we would put the computer outside inside the shed on the roof. This was definitely the simpler route and allowed us to spend more time making everything in the network look neat. With the computer up and running we were able to test all sixteen sensors on the roof and make sure everything was working properly. With everything up and running we turned the network over to our liaison who considers it to be a success.

4.4.4 Conclusion

Despite the delays in the creation and use of the temperature network we still consider it to be a very useful part of our project. The data we gained to use in the micro cost analysis was not available anywhere else, and the data that will be gathered in the future may help to further green roofs in Puerto Rico. The ease of use and accuracy of the network are very important factors in the networks future use and we believe that we have done as much as we can in both these respects with the budget we had. Hopefully our temperature network will remain in use long into the future and help future studies of green roofs in Puerto Rico.

4.5 Micro and Macro Cost Analysis Results

Both the micro and macro cost models showed benefits to individuals and to society, respectively. The energy model showed a significant energy savings for the green roof over the traditional roof. The life-cycle cost analysis model showed savings for a green roof over the 40-year time frame. The macro analysis showed benefits to society in the form of decreased urban runoff, decreased energy consumption, and mitigation of the urban heat-island effect.

4.5.1 Micro Cost Analysis Results

This section outlines the results from the life-cycle cost model for a green versus a traditional roof. It encompasses all tangible costs related to both roofs.

Installation Costs for Traditional Roofs

Cost estimates for the traditional roof were obtained via fax from local roofing contractors and via email from American firms. These costs are given in Figure 29. The costs were referenced to similar systems in RSMeans' 2003 Building Construction Cost Data and found to be reasonable.

Company	Location	Cost per Square Foot	Lifespan	Description of System Provided
D Waterproofing	San Juan, Puerto Rico	$4.25	10 yrs	2-ply modified bitumen membrane over 60 mm urethane insulation, installed
Caribbean Roofing	San Juan, Puerto Rico	$3.55	10 yrs	Asphaltic 2-component membrane, 100% elastomeric, over 60 mm urethane insulation, installed
Suffolk Construction	Boston, Massachusetts	$11.00	20 yrs	EPDM, including all roofing components and insulation

Figure 29 - Installation Costs for Traditional Roofs

Installation Costs for Green Roofs

Installation costs for green roofing systems were obtained via email from a leading UK firm, a US firm, and a Canadian Firm. Some companies provided costs broken down by roofing component and others only provided general costs per square foot for the entire assembly. Where it was not clear how much of a material's cost was dedicated to supply and how much was dedicated to installation, RSMeans' Cost Data was consulted for labor productivity and cost of comparably installed materials. Costs for each respective company's entire green roof system are given on a square foot basis in Figure 30. Figure 31 provides the component-based cost estimate that was used in the life-cycle cost analysis. The prices given in Figure 30 correspond to materials taken from a variety of sources. Price quotes received from each company did not cover the same set of items in all cases, so holes were filled in using average prices from the other estimates and RSMeans. Please see Appendix G for listings of quotes received from each company.

Company	Location	Cost per Square Foot	Lifespan	Description
Bauder	UK	$17-$19	40+	All items above structural deck, including seeded green roof (applications >10,000 SF)
Bauder	UK	$19-$21	40+	All items above structural deck, including pre-grown green roof mat (applications <10,000 SF) Please see Appendix G for details.
Hydrotech	US	$17.50	40+	All items above structural deck. Please see Appendix G for details.
ELT Green Roofs	Canada	$15.50	40+	All items above structural deck. Please see Appendix G for details.

Figure 30 - Green Roof General Installation Costs

Item Type	Item Description	Source	Material Cost	Labor Cost	O&P	Total
Plants	Various	Pennock Growers	$3.00	$1.00	$0.40	*$4.40*
Growing Medium	Limestone& Soil		$1.00	$0.20	$0.12	*$1.32*
Filter Membrane	System Filter SF	Hydrotech	$0.40	$0.13	$0.05	*$0.58*
Drainage Layer	FD40	Hydrotech	$2.57	$1.03	$0.36	*$3.96*
Moisture Mat	SSM45	Hydrotech	$0.80	$0.16	$0.10	*$1.06*
Root Barrier	WSF40	Hydrotech	$0.38	$0.13	$0.05	*$0.56*
Waterproofing Membrane	MM6125	Hydrotech	$1.73	$0.80	$0.25	*$2.78*
protection and separation	Hydroflex 10	Hydrotech	$0.33	$0.16	$0.05	*$0.54*
Thermal Insulation	RSMeans	RSMeans	$1.35	$0.20	$0.16	*$1.71*
Vapor Control	RSMeans	RSMeans	$0.06	$0.06	$0.01	*$0.14*
Total			*$11.62*	*$3.87*	*$1.55*	***$17.04***

Figure 31 - Itemized Green Roof Installation Cost Used In Life Cycle Cost Analysis

Replacement Costs for Traditional and Green Roofs

Roof resealing records were obtained from the President's Office at the University of Puerto Rico. These costs were quoted at $6.00 per square foot. This figure, slightly higher than original installation costs, makes sense because the existing surface must be removed and disposed of before a replacement is placed.

The waterproofing layers on green roofs have been examined for roofs that have been in place for over 60 years, and found to be in excellent functional condition due to the shielding of the sun's rays by the soil and vegetation (Osmundson, 1999). Thus, there are no replacement costs in the 40 year time frame that we are working with in this model.

Maintenance Costs for Traditional and Green Roofs

There are no maintenance costs for traditional roofs. They are simply left alone to deteriorate over their lifespan (10 years for the traditional roofing system used in this model). There are slight annual maintenance costs involved with a green roof. This is due to the roofs' slight needs for weeding and trimming, usually a one man crew for about two days per year for a 10,000 square foot roof (Alumasc-ZinCo, 2003). The cost was estimated using RSMeans to be approximately $0.02 per square foot per year.

Additional Structural Costs for Green Roofs

The results of the analysis of additional structural costs due to the addition of a green roof are shown below. Figure 32 utilizes Equation 3-1 from Methodology Section 3.3.1 to determine this cost.

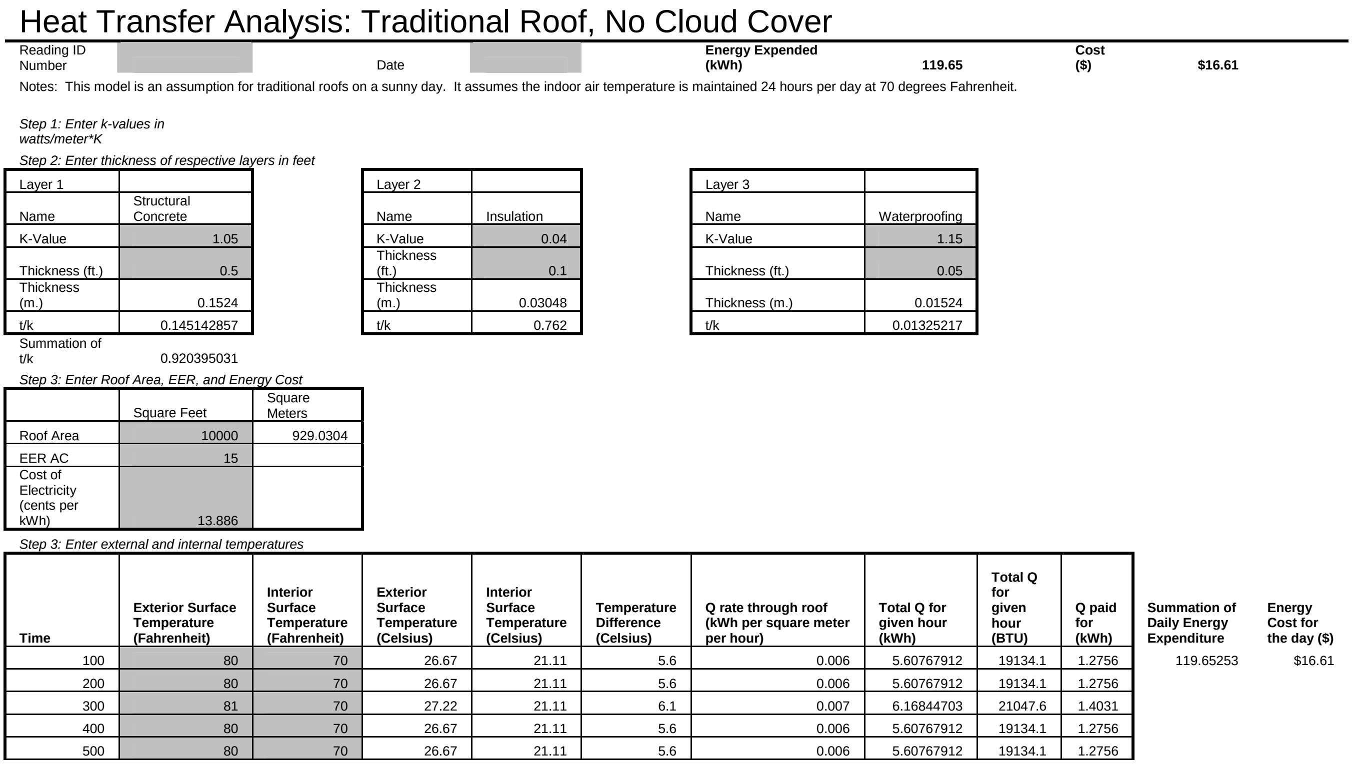
Building Type	Cost per Square Foot	Percentage of that Cost Devoted to Overall Building Structure	Cost per Square Foot of Building for all Structural Members	Cost per Square Foot Roof due to 30% Reduction	Cost of Additional Weight Imposed by Green Roof (20%)
Mid-Rise Apartments	$74.30	14%	$10.50	$7.35	$1.47
High-Rise Apartments	$85.25	14%	$11.90	$8.33	$1.67
Bank	$132.00	14%	$18.48	$12.94	$2.59
College Classroom/ Administration	$140.00	14%	$19.60	$13.72	$2.74
Mid-Rise Office	$84.00	14%	$11.76	$8.23	$1.65
High-Rise Office	$107.00	14%	$14.98	$10.49	$2.10
Average	$103.83		$14.54	$10.18	**$2.04**

Figure 32 - Square-Foot Cost of Structural Members to Support Additional Green-Roof Loadings

The final result of this process was the determination of the cost of additional structural reinforcement to support the additional weight imposed by a green roof. By determining the approximate percentage of overall building cost that is devoted to roof structural support, general square foot costs for a typical building, and the percentage weight increase due to green roofs, we were able to determine that installing a green roof causes an increase of approximately $2.04 per square foot of roof area.

Energy Cost Results

Temperature data was recorded for both the traditional roof and the green roof by placing the sensors in the locations described in Section 3.2. Temperatures were recorded for a 24 hour cycle and then hourly averages were compiled. These averages became input for the heat transfer model. The model calculated the heat transfer through the roof and the cost of electricity required for cooling. A sample daily heat transfer and electricity cost chart for both roofs is shown in Figure 33 and 34. This figure has been simplified from the actual version for demonstration purposes. On the actual worksheet, data is recorded for hour 100 through hour 2400, instead of the first four hours shown here. The actual worksheets for both roofs for the model cloudy and sunny day can be seen in Appendix H. The gray fields represent user inputs, and the rest of the cells convert the data into the output, the estimated energy and monetary expenditures. The output of these sheets can be found under the title line for the respective sheets. Figure 3shows a set of output for a traditional roof on a day with no cloud cover and Figure 34 shows a set for a green roof on a day with no cloud cover. This model was also run for a day with 100% cloud cover, resulting in another set of outputs for both the green and traditional roofs. It is important to note that Figures 33 and 34 represent heat transfer for a traditional and a green roof on a sunny day, so the energy savings of a green roof over a traditional roof is higher than it would be for the annual model, which encompasses sunny *and* cloudy day.



Heat Transfer Analysis: Traditional Roof, No Cloud Cover

Reading ID Number		Date		**Energy Expended (kWh)**	**119.65**	**Cost ($)**	**$16.61**

Notes: This model is an assumption for traditional roofs on a sunny day. It assumes the indoor air temperature is maintained 24 hours per day at 70 degrees Fahrenheit.

*Step 1: Enter k-values in watts/meter*K*

Step 2: Enter thickness of respective layers in feet

Layer 1	
Name	Structural Concrete
K-Value	1.05
Thickness (ft.)	0.5
Thickness (m.)	0.1524
t/k	0.145142857

Layer 2	
Name	Insulation
K-Value	0.04
Thickness (ft.)	0.1
Thickness (m.)	0.03048
t/k	0.762

Layer 3	
Name	Waterproofing
K-Value	1.15
Thickness (ft.)	0.05
Thickness (m.)	0.01524
t/k	0.01325217

Summation of t/k 0.920395031

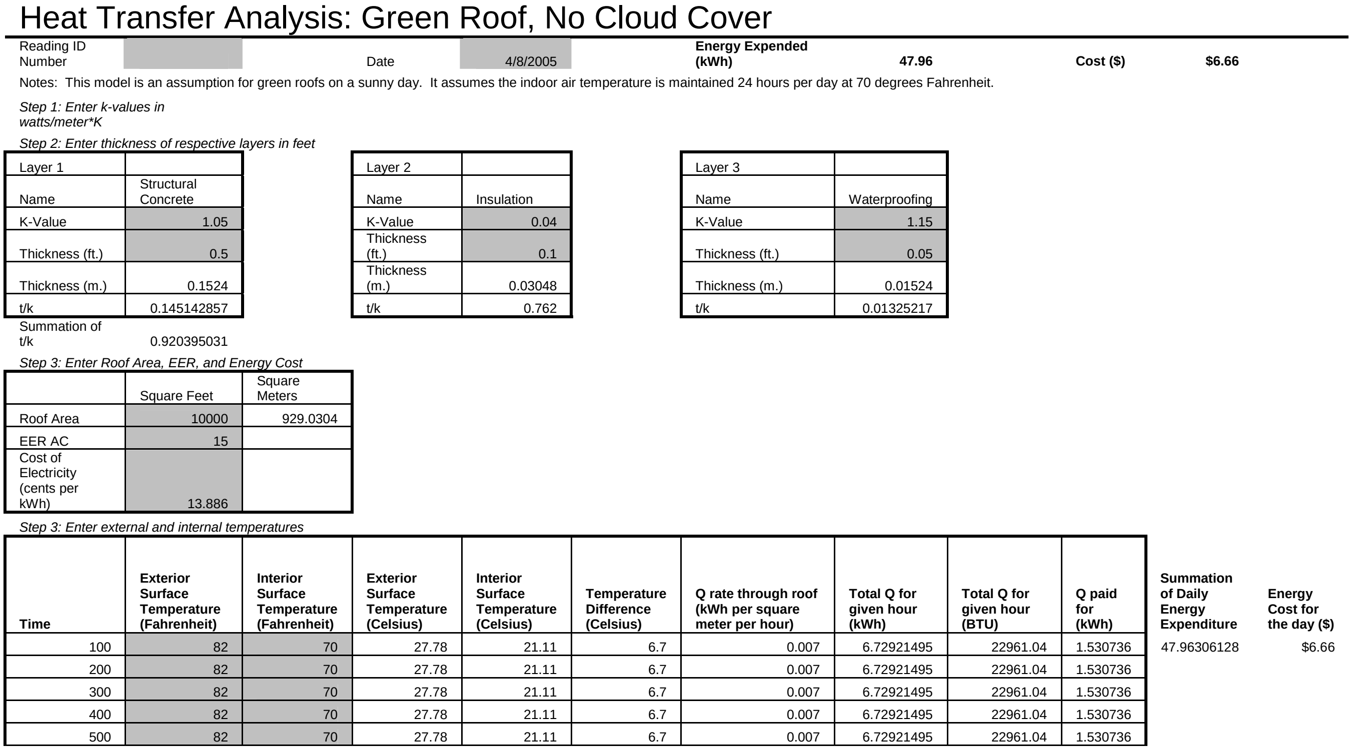
Step 3: Enter Roof Area, EER, and Energy Cost

	Square Feet	Square Meters
Roof Area	10000	929.0304
EER AC	15	
Cost of Electricity (cents per kWh)	13.886	

Step 3: Enter external and internal temperatures

Time	**Exterior Surface Temperature (Fahrenheit)**	**Interior Surface Temperature (Fahrenheit)**	**Exterior Surface Temperature (Celsius)**	**Interior Surface Temperature (Celsius)**	**Temperature Difference (Celsius)**	**Q rate through roof (kWh per square meter per hour)**	**Total Q for given hour (kWh)**	**Total Q for given hour (BTU)**	**Q paid for (kWh)**	**Summation of Daily Energy Expenditure**	**Energy Cost for the day ($)**
100	80	70	26.67	21.11	5.6	0.006	5.60767912	19134.1	1.2756	119.65253	$16.61
200	80	70	26.67	21.11	5.6	0.006	5.60767912	19134.1	1.2756		
300	81	70	27.22	21.11	6.1	0.007	6.16844703	21047.6	1.4031		
400	80	70	26.67	21.11	5.6	0.006	5.60767912	19134.1	1.2756		
500	80	70	26.67	21.11	5.6	0.006	5.60767912	19134.1	1.2756		

Figure 33 - Sample Output for Traditional Roof, No Cloud Cover



Heat Transfer Analysis: Green Roof, No Cloud Cover

Reading ID Number		Date	4/8/2005	Energy Expended (kWh)	47.96	Cost ($)	$6.66

Notes: This model is an assumption for green roofs on a sunny day. It assumes the indoor air temperature is maintained 24 hours per day at 70 degrees Fahrenheit.

*Step 1: Enter k-values in watts/meter*K*

Step 2: Enter thickness of respective layers in feet

Layer 1	
Name	Structural Concrete
K-Value	1.05
Thickness (ft.)	0.5
Thickness (m.)	0.1524
t/k	0.145142857

Layer 2	
Name	Insulation
K-Value	0.04
Thickness (ft.)	0.1
Thickness (m.)	0.03048
t/k	0.762

Layer 3	
Name	Waterproofing
K-Value	1.15
Thickness (ft.)	0.05
Thickness (m.)	0.01524
t/k	0.01325217

Summation of t/k 0.920395031

Step 3: Enter Roof Area, EER, and Energy Cost

	Square Feet	Square Meters
Roof Area	10000	929.0304
EER AC	15	
Cost of Electricity (cents per kWh)	13.886	

Step 3: Enter external and internal temperatures

Time	Exterior Surface Temperature (Fahrenheit)	Interior Surface Temperature (Fahrenheit)	Exterior Surface Temperature (Celsius)	Interior Surface Temperature (Celsius)	Temperature Difference (Celsius)	Q rate through roof (kWh per square meter per hour)	Total Q for given hour (kWh)	Total Q for given hour (BTU)	Q paid for (kWh)	Summation of Daily Energy Expenditure	Energy Cost for the day ($)
100	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736	47.96306128	$6.66
200	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		
300	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		
400	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		
500	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		

Figure 34 - Sample Output for Green Roof, No Cloud Cover

As can be seen from the heat transfer worksheets for the traditional and green roofs, the traditional roof passed to the building interior almost three times the energy that was transferred by its green counterpart. Examination of the sheets reveals that the summation (t/k) for both roofs was the same. The reason that considerably less heat was transferred by the green roof is the lower exterior temperature observed for that system. This can not be seen from the sample sheets in Figures 33 and 34, because the high-intensity sunlight hours of late morning and afternoon are not shown.

Since we were not able to measure temperatures over the course of a year, we had to find a way to expand our limited data to approximate fluctuations in temperature and sunlight exposure over the changing seasons. Weatherbase.com was used as a basis for expanding this data to a yearly approximation. This website gives monthly averages for temperature and cloud cover over a 40 year sample space. The worksheets for this analysis are displayed in Figures 35 and 36. Please note that the outputs from the daily heat transfer models of Figures 33 and 34 have become inputs for each roofing system in the annual heat transfer model. The other two inputs came from sheets similar to Figures 33 and 34, but with the results from a cloudy day instead of a sunny day.

Figures 35 and 36 make use of the cloud cover and temperature records described above. We first took the numbers for probability of cloud cover, and split the days in the month up between no cloud cover and 100% cloud cover. This can be seen in the 4th and 5th columns of Figures 35 and 36. We then looked at the monthly temperature data and set April as the datum, since that was the month in which we took our data. All other months were then given a percent deviation from this datum temperature. Then, the heat transferred through each respective roof for the measured sunny and cloudy day in April was scaled by this percent deviation. The results of this scaling can be seen in the 9th and 10th column of Figures 35 and 36. Then, the daily energy expenditure, now corrected for monthly temperature deviation, was multiplied by its respective "type of day" as appropriate, whether sunny or cloudy. For example, heat transfer through a 10,000 square foot traditional roof on a sunny day in January results in 115.17 kWh of energy expended to maintain room temperature. According to Weatherbase.com, the probability of sunshine for January yields 21.08 sunny days. Thus, the total energy expended on sunny days in January is (115.17*21.08 = 2428 kWh). The same was done for cloudy days in January, and then sunny and cloudy days for the remaining 11 months. The results were added together for each month, and then the totals from each month were added to yield total energy expended as a result of heat transfer through each roof on an annual basis. For a typical year, the traditional roof incurred an expenditure of $0.54 per square foot whereas the green roof incurred a cost of only $0.23 per square foot, representing a savings of over 50%.

Annual Energy Expenditure for Traditional Roof

Annual Energy Expended (kWh) **38712** **Cost ($)** **$5,375.58**

Notes: This model takes values of heat transferred through a traditional roof on a cloudy day and a sunny day, and uses monthly temperature data and cloud cover records to approximate the energy transferred through the roof for the year.

Input from traditional roof sunny and cloudy days

Base Month Sunny Day Energy Expenditure (kWh)	119.65
Base Month Cloudy Day Energy Expenditure (kWh)	78.20
Cost per kWh (cents)	13.886

Month	**Days in Month**	**Average Possibility of Sunshine**	**Sunny Days**	**Cloudy Days**	**Average Temperature**	**Temperature Deviation from Base**	**Percent Deviation**	**Sunny Day Energy Expenditure, kWh (Corrected for Monthly Temperature Fluctuation)**	**Cloudy Day Energy Expenditure, kWh (Corrected for Monthly Temperature Fluctuation)**	**Monthly Expenditure From Sunny Days (kWh)**	**Monthly Expenditure From Cloudy Days (kWh)**	**Total Monthly Energy Expenditure (kWh)**
January	31	68	21.08	9.92	77	-3	-0.0375	115.17	75.26	2427.69	746.61	3174.30
February	28	71	19.88	8.12	77	-3	-0.0375	115.17	75.26	2289.49	611.13	2900.63
March	31	76	23.56	7.44	78	-2	-0.025	116.66	76.24	2748.54	567.23	3315.77
April (Base)	30	71	21.3	8.7	80	0	0	119.65	78.20	2548.60	680.30	3228.90
May	31	63	19.53	11.47	81	1	0.0125	121.15	79.17	2366.02	908.11	3274.13
June	30	64	19.2	10.8	82	2	0.025	122.64	80.15	2354.76	865.62	3220.38
July	31	68	21.08	9.92	83	3	0.0375	124.14	81.13	2616.86	804.78	3421.64
August	31	67	20.77	10.23	83	3	0.0375	124.14	81.13	2578.38	829.93	3408.31
September	30	62	18.6	11.4	83	3	0.0375	124.14	81.13	2308.99	924.85	3233.85
October	31	63	19.53	11.47	82	2	0.025	122.64	80.15	2395.23	919.32	3314.55
November	30	61	18.3	11.7	80	0	0	119.65	78.20	2189.64	914.88	3104.52
December	31	60	18.6	12.4	78	-2	-0.025	116.66	76.24	2169.90	945.38	3115.28
											Annual Energy Expenditure (kWh)	**38712.26**
											Cost of energy ($)	**$5,375.58**
											Cost of Energy per Square Foot	$0.54

Figure 35 - Annual Approximation of Heat Transferred Through Traditional Roof

Annual Energy Expenditure for Green Roof

Annual Energy Expended (kWh) **16870** **Cost ($)** **$2342.55**

Notes: This model takes values of heat transferred through a green roof on a cloudy day and a sunny day, and uses monthly temperature data and cloud cover records to approximate the energy transferred through the roof for the year.

Input from traditional roof sunny and cloudy days

Base Month Sunny Day Energy Expenditure (kWh)	47.96
Base Month Cloudy Day Energy Expenditure (kWh)	42.22
Cost per kWh (cents)	13.886

Month	**Days in Month**	**Average Possibility of Sunshine**	**Sunny Days**	**Cloudy Days**	**Average Temperature**	**Temperature Deviation from Base**	**Percent Deviation**	**Sunny Day Energy Expenditure, kWh (Corrected for Monthly Temperature Fluctuation)**	**Cloudy Day Energy Expenditure, kWh (Corrected for Monthly Temperature Fluctuation)**	**Monthly Expenditure From Sunny Days (kWh)**	**Monthly Expenditure From Cloudy Days (kWh)**	**Total Monthly Energy Expenditure (kWh)**
January	31	68	21.08	9.92	77	-3	-0.0375	46.16	40.64	973.15	403.14	1376.29
February	28	71	19.88	8.12	77	-3	-0.0375	46.16	40.64	917.75	329.99	1247.74
March	31	76	23.56	7.44	78	-2	-0.025	46.76	41.17	1101.76	306.28	1408.04
April (Base)	30	71	21.3	8.7	80	0	0	47.96	42.22	1021.61	367.34	1388.95
May	31	63	19.53	11.47	81	1	0.0125	48.56	42.75	948.43	490.35	1438.78
June	30	64	19.2	10.8	82	2	0.025	49.16	43.28	943.91	467.41	1411.32
July	31	68	21.08	9.92	83	3	0.0375	49.76	43.81	1048.98	434.56	1483.53
August	31	67	20.77	10.23	83	3	0.0375	49.76	43.81	1033.55	448.14	1481.69
September	30	62	18.6	11.4	83	3	0.0375	49.76	43.81	925.57	499.39	1424.96
October	31	63	19.53	11.47	82	2	0.025	49.16	43.28	960.14	496.40	1456.54
November	30	61	18.3	11.7	80	0	0	47.96	42.22	877.72	494.01	1371.73
December	31	60	18.6	12.4	78	-2	-0.025	46.76	41.17	869.81	510.47	1380.28

Annual Energy Expenditure (kWh)	**16869.85**
Cost of energy ($)	**$2,342.55**
Cost of Energy per Square Foot	$0.23

Figure 36 - Annual Approximation of Heat transferred Through Green Roof

Similar studies, such as one carried out in the United Kingdom by English Nature Research Reports, displayed an energy savings of approximately 2 liters of fuel oil per year per square meter (English Nature, 2003). At a cost of $2.20 per gallon of fuel oil and in converted units, this works out to about $0.11 per square foot. The roof in San Juan showed an energy savings of $0.31 per square foot, almost three times the energy savings realized on European green roofs through the English Nature study. The reason for the higher savings in San Juan can be attributed to the fact that the nature of green roofs makes them more energy efficient in summer months than in winter months. In summer months, a building benefits not only from the additional insulating value of the materials, but also from the evaporation and transpiration of water. In winter, the benefits of green roofs are limited to the extra material insulation they provide. When this is considered, it makes sense that the San Juan green roof provided three times the energy savings than did the European green roof, since the San Juan green roof is subject to twelve months of summer temperatures as opposed to five or six.

Limitations of the Heat Transfer Model

The energy cost model was intended to model the actual heat transfer through the roof as accurately as possible given available resources. It is an approximation of real-life and has its imperfections. Some imperfections are implicit in the model, and others involve the data entry.

The model itself has certain aspects that could be improved in future studies. The first is the assumption that the vehicle for all heat transfer at the roof is conduction. This is untrue, since radiation, convection, and the latent heat of vaporization of water also play important roles. The conductive heat transfer equation, as applied, should capture the heat transfer accurately, but a model that takes into account the other modes of heat transfer would arrive at more accurate results. Another approximation implicit in the heat transfer model is the thermal resistance value of the composite roof. This model used the same value for both the traditional and green roof. In reality, the green roof provides additional conductive insulation because it contains several layers not present in traditional roofs, including a drainage, moisture retention, substrate, and plant layer. Ignoring the effects of these layers on the green roof certainly would understate the energy savings of the green roof.

There were also imperfections involved with the data entry which could be responsible for the lower-than-expected energy savings. We were only able to record temperature data for a few days in April, and then we had to use known temperature patterns to simulate data for the rest of the year. We were able to obtain a good cross section of weather patterns in those few days, ranging from hot, sunny days to overcast days to rainy days, and several combinations of the three. We then used historical cloud cover and temperature data to simulate the remaining days and months of the year. More accuracy could be brought to the study by monitoring actual temperature data for an entire year and using this data instead of simulated data.

Life Cycle Cost Analysis Results

After all the different costs associated with a traditional roofing system vs. a green roof were collected, they were input into the life cycle cost analysis model. The costs for the traditional and green roof for a 40-year span are given in Figure 37 and 38, respectively.

Type of Cost	Frequency	Cost per Square Foot
Installation	One-time	$4.25
Maintenance	Never	-
Replacement	10 year interval	$6.00
Energy	Annual	$0.54

Figure 37 - Life-Cycle Square foot costs for Traditional Roof

Type of Cost	Frequency	Cost per Square Foot
Installation	One-time	$17.04
Additional Structural Support	One-time	$2.04
Maintenance	Annual	$0.02
Replacement	Never (40 year span)	-
Energy	Annual	$0.23

Figure 38 - Life-Cycle Square Foot Costs for Green Roof

The life-cycle cost analysis model placed each of these costs into its appropriate location for years 0-40, and took into account the time-value of money, assuming a 3% inflation rate. The present values at year 0 of the preceding costs in time for green and traditional roofs are given in Figure 39. This chart represents the costs incurred for a 10,000 square foot roof.

Type of Cost	Traditional Roof Cost	Green Roof Cost
Installation	$42,500	$170,429
Additional Structural Support	-	$20,352
Maintenance	-	$4,823
Replacement	$105,663	-
Energy	$129,631	$56,490
Total	$277,794	$252,093

Figure 39 - Life-Cycle Costs for 10,000 Square Foot Roof for 40 Year Span (adjusted for Time-Value of Money)

As can be seen from the figure above, the green roof showed a significant savings over the traditional roof over the 40-year period. The traditional roof's final cost was $27.78 per square foot and the green roof's cost was $25.21 per square foot. This represents a life-cycle savings of about 10%. The life cycle costs were calculated using the life cycle cost model seen in Appendix I.

Figure 40 shows the cumulative life-cycle costs for the green and traditional roofs. The stepped line represents the cumulative cost of a traditional roof. Note that its installation costs start out very low, but the cost climbs rapidly over time due to replacement costs (represented by each step) and energy costs (represented by more horizontal portions). The smoother top line represents the green roof described in Figure 38. The installation costs are significantly higher than for traditional roofs, but the only additional costs are annual energy costs which accrue at a much slower rate than that of traditional roofs (note the slope of the "flat" portion of traditional roof costs compared to the curve for green roofs). The other smooth line represents the same green roof, but with a government incentive of 15% of the installation cost of the green roof (about $2.50). This is not out of the question, as German incentives have been reported to be as high as $5.00 per square foot (see background section). The payback period for the non-incentive green roof is 30 years, and the payback period for the 15% subsidized green roof is only 20 years.

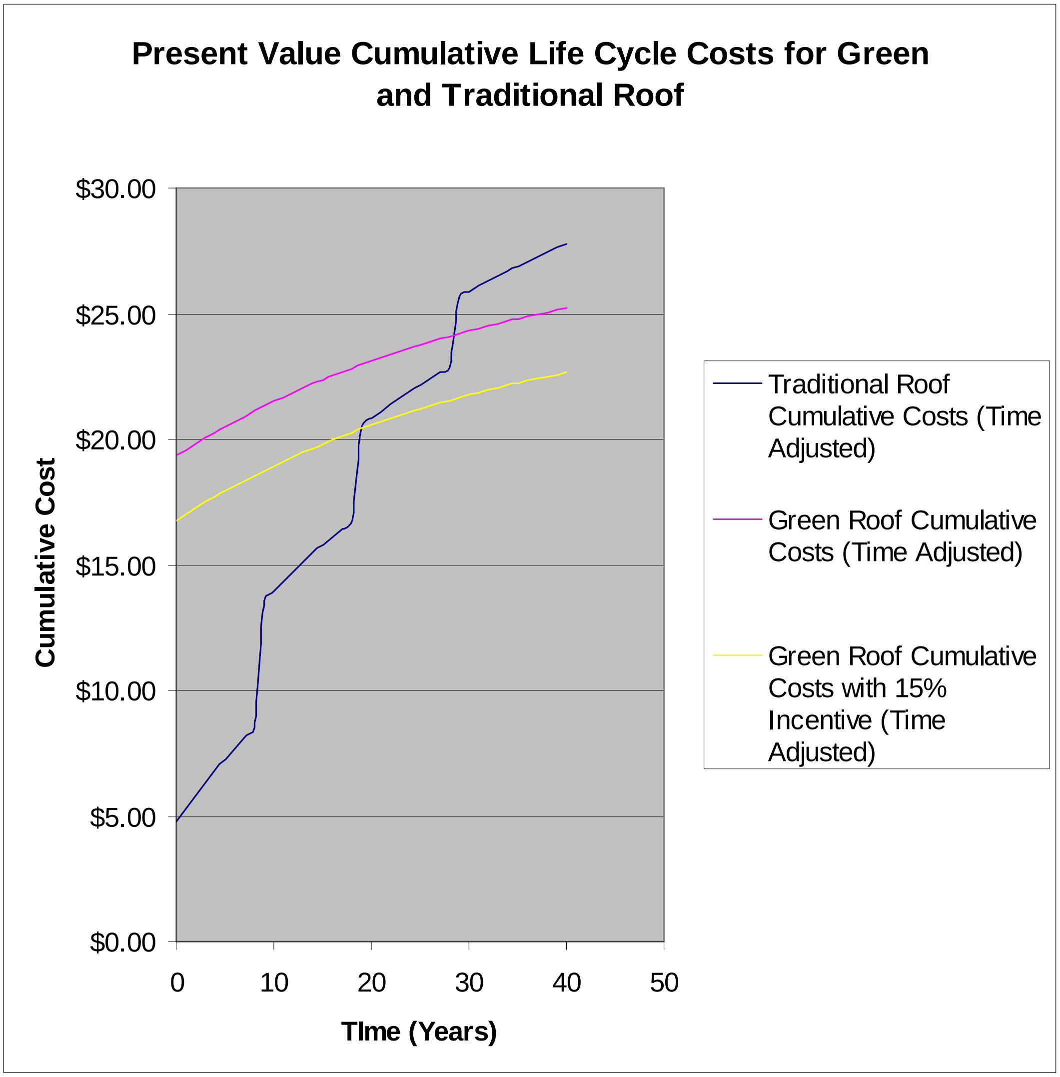


Figure 40 - Present Value Cumulative Life Cycle Costs for Green and Traditional Roof

Analysis and Recommendations Regarding Life Cycle Cost Model

It is interesting to note the comparison of our completed life-cycle cost comparison to similar studies, such as studies conducted elsewhere or that found in Background Section 2.4.4. It seems that the background model is flawed, since its quote for the cost of a green roof installation is lower than the lowest quote we received and about two-thirds of the average quote we received. In addition, the cost of the traditional roofing system is more than double the highest quote we received. Although that study didn't include energy savings costs, it suggests a 10-20% annual energy savings cost whereas our model yielded a 50% annual energy savings.

From an installation and materials standpoint, it seems that the disparity between estimated green roof costs and estimated traditional roof costs is higher for San Juan than what had been found in other studies, making green roofs a less viable option from this perspective. However, as noted previously, the savings on green roof energy costs were found to be three times the savings documented in Europe. The life cycle 10% savings of a green roof in San Juan over a traditional roof in San Juan is significant in itself. However, this savings does not even take into account the savings in social cost and additional social benefits of green roofs.

Other factors which add to the value of the green roof are benefits to society and the environment, including a reduction of the roof's contribution to the urban heat-island effect, a reduced strain on municipal drainage systems due to the roof's water retention ability, reduced air pollution, and the aesthetic appearance of a properly maintained green roof. As has been mentioned before, these intangible benefits often translate into tangible benefits for owners of green roofs in the form of government incentive programs. When the government is aware of the positive effects that green roofs contribute to society, they often institute incentive programs to encourage their construction.

4.5.2 Macro Cost Analysis Results

Each of the following sections poses theoretical cases in which green roofs are installed over one, two, five, and ten percent of existing traditional roofs in San Juan. For each of the three macro benefits outlined below, the total square footage of roof area in San Juan was calculated by assuming that 20% of the 43 square miles defined as the San Juan Metropolitan Area are currently covered by roofs, as outlined in Methodology Section 3.2.2.

Heat Island Effect

The results of influence on the urban heat island effect for one, two, five, and ten percent implementation of green roofs over traditional roofs in San Juan are given in Figure 40. The square feet of impermeable space was calculated by adding the figures for roof and pavement area, 21% and 26% of total urban area, respectively, given by the Akbari study. This was multiplied by the area of San Juan and converted to square feet. The square footage of green roofs as a percentage of the total impermeable area was then calculated. Then, the five degree difference in the average temperature of San Juan as compared to its surrounding areas was decreased by this percentage. The corresponding temperature decrease, in degrees Fahrenheit, is shown below.

% Roofs Greened in San Juan	Square Feet of Green Roofs (Millions)	Square Feet of Impermeable Space (Millions)	Percentage of Impermeable Space Occupied by Green Roofs	Decrease in Average Annual Temperature (°F)
1%	2.4	560	0.43%	0.021
2%	4.8	560	0.85%	0.043
5%	12	560	2.13%	0.106
10%	24	560	4.26%	0.213

Figure 41 - Local Temperature decrease for Theoretical Percentages of Roofs Greened

These temperature decreases may be seen as very small, but such a decrease may provide considerable savings in heating costs and provide the additional benefit of decreasing human impact on the environment. This technology can be very useful in a city where it is difficult to find ways to increase vegetation. Green roofs can provide a valuable part of a greater scheme to increase vegetation cover in urban areas.

Runoff Effects

It was found that 100% of rainfall in 11 out of the 12 months of the year in San Juan occurred in events of less than 2” in 24 hours. However, in the heaviest rainfall month, September, it was found that only 26% of rainfall fell within this category. The heavy rainfall of September was due to Hurricane Hortense which produced over 8” of rainfall in one day alone. Whereas 90% of rainfall in Philadelphia occurs in events of less than 2” in 24 hours, it was found that only 80%, or 45 out of 56 inches of rainfall in Puerto Rico fulfills this requirement. It should come as no surprise that rainfall events tend to be more severe in Puerto Rico than they are in Philadelphia. Even so, in non-hurricane situations, it appears that a green roof in San Juan will attenuate runoff as effectively as did the green roof in the Philadelphia study. The Philadelphia study found that green roofs prevent 60% of runoff from reaching municipal sewer systems. In Puerto Rico, 80% of the rainfall will generate runoff that behaves this way. Assuming that 60% of this rainfall will be retained by the green roof, 27 out of 56 inches of annual rainfall incident on the green roof will never reach the sewer system (0.8 * 0.6 * 56 inches = 27 inches). This is equivalent to 1.125 cubic feet (17 gallons) per square foot of roof area. For a 10,000 square foot roof, this means that the local drainage network will handle 170,000 fewer gallons annually. Furthermore, the runoff that does reach the sewer system reaches it in a lower peak volume and spread out over a longer period of time. Figure 42 shows the amount of runoff that could be prevented by implementation on one, two, five, and ten percent of the roof area in San Juan. The benefits of this effect to a city that frequently issues flash flood warnings due to thunderstorms within municipal limits are quite valuable. Strategically placed green roofs in problem areas could certainly make an impact on the functioning of sewer systems in troublesome areas.

% Roofs Greened in San Juan	Square Feet of Green Roofs (Millions)	Annual Gallons of Runoff Attenuated (Millions)
1%	2.4	41
2%	4.8	82
5%	12	204
10%	24	408

Figure 42 - Gallons of Runoff Prevented from Reaching Sewer system for Theoretical Percentage of Roofs Greened

Macro Energy Savings

The results of energy savings for one, two, five, and ten percent implementation of green roofs over traditional roofs in San Juan are given in Figure 43.

% Roofs Greened in San Juan	Square Feet of Green Roofs (Millions)	Annual Energy Savings: 2.24 kWh per Square Foot (Million kWh)	Annual Energy Savings: $0.14 per kWh ($)
1%	2,397,542	5.4	$745,746.93
2%	4,795,085	10.8	$1,491,493.86
5%	11,987,712	27	$3,728,734.66
10%	23,975,424	54	$7,457,469.32

Figure 43 - Energy and Cost Savings for Theoretical Percentages of Roofs Greened

For perspective, Puerto Rico consumed 141 billion kWh of energy in 2002, with 22.1 billion of that generated in domestic oil-burning facilities (Puerto Rico Fact Sheet, 2004). Ten percent implementation of green roofs in San Juan would represent a savings of 0.25% of energy produced in domestic facilities.

4.6 Marketing Green Roofs in Puerto Rico

Our intentions for marketing green roofs in Puerto Rico were severely limited by several situations that were beyond our control. The first difficulty was the unfavorable weather conditions and poor condition of the green roof upon our arrival. The second difficulty encountered was our inability to access the green roof for a period of one week due to a new lock being placed on the door that was used to access the roof. The most severe difficulty was encountered when students at Puerto Rico went on strike and closed down the campus. This prevented access to the roof for a week, and then made access very difficult for the succeeding two weeks. Because of these difficulties, we were not able to obtain the data necessary for our heat transfer model. Without this data, we could not conduct meetings with our three target groups as planned. We were only able to schedule two interviews with people from our key sectors. The proceedings of these interviews are recorded below.

4.6.1 Interview with McNeil Pharmaceuticals

Contacting the large corporation McNeil, after an initial contact with project engineer Mr. Jean S. López, brought an opportunity for a potential consumer's opinion on green roofs in their large industry and manufacturing facilities in Las Piedras, Puerto Rico. McNeil has deep roots in the pharmaceutical industry from the early 1930s and has driven to the top through their sales becoming a corporation at the forefront in the world's proprietary pharmaceutical industry.

This opportunity to start incorporating large business's opinions on savings along with advantages and disadvantages, through their perspective, on green roofs helped us with new ideas and problems that we had not thought of integrating into our experiments. Mr. Jean S. López had contacted me back after a follow up email sent to him with our ideas and positive aspects of green rooftops. In his response he stated that Johnson and Johnson is a very pro-environmental multinational corporation, having environment as one of its top priorities in their Credo. But the bottom line is that as a private corporation, their goal is to maximize profits, so they need heavy reasons on both environmental and financial fronts to consider that type of endeavor. Also being a manufacturing facility their other concern was due to the nature of their operations in pharmaceuticals and healthcare products, investing a significant amount of resources trying to avoid birds and other types of animals in the perimeter of their outside plants, and discouraged the possibility of encouraging these animals onto their rooftops.

This however did encourage new ideas to be looked into in the field of green roofs, but due to our restricted timeline we will not be able to construct any feasible options before our project is over. This leaves a possible new project to be looked into further, due to the high amount of pharmaceutical companies in Puerto Rico. Ending our conversation Mr. Jean S. López still commented on the opportunities that green roofs present in the high use of air conditioning to the commercial district other than pharmaceuticals, but hopes that there can be progress to resolve this issue of keeping “pest control” manageable and controlled on green roofs for maybe a future use with their company.

4.6.2 Interview with Danosa, Potential Supplier and Installer

This interview took place with Danosa, a worldwide leader in waterproofing technology. Dasona began in Japan as a pioneer in the green roof industry there. Danosa has roots in Spain and Japan with branch offices elsewhere, including its offices in Puerto Rico.

This interview took place on April 8, 2005, with Mr. Felix A. Romero, a manager in the technical commercial department at Danosa’s offices in the Luchetti Industrial Complex in Bayamon, Puerto Rico. We had originally expected that Danosa Puerto Rico could supply some of the materials that are necessary but not unique to green roofs - such as the waterproofing, insulation, and root barriers. However, it soon became clear that Danosa and Mr. Romero had a far deeper experience and interest in materials unique to green roofs and green roofs themselves.

Mr. Romero began by briefly introducing Danosa’s history, and then moved on to Danosa’s prior involvement with the green roof at the University of Puerto Rico. It came to our attention that Danosa had been a candidate for installation of the green roof at Puerto Rico, but had lost out to the German company in the final stages.

After this discussion, the conversation turned to green roofs in general. Mr. Romero expressed that not very many people know very much about green roofs, known locally as naturacion. This coincided with our presumption of lack of knowledge as a significant barrier to green roof construction. However, Mr. Romero expressed great enthusiasm for the prospects of green roofs in Puerto Rico and reinforced our understanding that many people shared this view yet simply needed to see data from a local study. The few people that are aware of this technology are generally quite aware of its benefits, but they would like to see data collected locally before investing in a green roof.

Mr. Romero then proceeded to demonstrate a sample green roof layering system provided by Danosa. This system, shown in Figure 44, includes (from the bottom layer up): particleboard base, 2 mm thick waterproofing layer, 3 mm thick root barrier made from modified asphalt with root-resistant additives, 1 cm thick DanoDrain (drainage and moisture retention layer), and a geotextile filter sheet. Soil and plants would be placed directly on top of this layer to complete the green roof assembly. This assembly was analogous to the systems provided by other companies from whom we received technical information, but specialized with Danosa’s own drainage and moisture retention layer. Danosa’s facilities in Puerto Rico have the capacity to manufacture all of these items except for DanoDrain, which must be imported from Spain. Mr. Romero agreed to try to provide us with a cost estimate of the various materials incorporated in the Danosa green roof, and also for a traditional roofing system for comparative purposes.

Figure 44 - Mock-Up of Danosa Green Roof Assembly

The meeting concluded after we were provided with a couple of names of developers and architects who have an interest in environmental concerns and may have some insights to share with us. The names provided were Dr. Michael Rigau, a professor in the Architecture Department at The Polytechnic University in Hato Rey, and Dr. Fernando Muno, an architecture professor at UPR.

Danosa seems to be a leading candidate to supply a green roof industry in Puerto Rico, complete with knowledgeable and enthusiastic employees and a strong economic base from which to encourage growth.

4.7 Suggestions for Future Studies

This section describes our suggestions for improvements on the following aspects of this study: temperature sensor network, energy and cost analysis model, and marketing. These sections generally assume availability of substantial funding. Many environmental agencies, including the EPA, offer grant programs to research groups with a well designed experimental plan. The preliminary results found in this study should provide a good background for a future, more in-depth study, and the experiments described in the next few sections aim to provide a basis for a plan for such a study.

4.7.1 Improvements to Temperature Sensor Network

The temperature sensor network built for this project suited our needs well enough; however, there are many improvements which could be made to create a better setup. Increasing the number of sensors would allow for a more accurate array of temperatures as well as allow for additional sensors to take different kinds of measurements, such as the ambient air temperature. The accuracy of the temperature measurements could be greatly improved as well if a more sensitive data acquisition device was used as well as a high quality power supply. With these improvements the temperature measurements could be accurate to about half a degree which is a great improvement over the current measurements.

The software used in this network could also be greatly improved to make it more user friendly. A simple program that could just be opened to initiate and display the temperature measurements could be made relatively easily by a programmer. This would eliminate any confusion that may be face by the future users. Obviously these improvements would drastically increase the cost of the network, but would make it much more useful.

4.7.2 Long-Term Improvements to Energy and Cost Analysis Model

The heat transfer model used in this study provided promising results for green roofs in Puerto Rico. These results should be followed up with a study that more accurately isolates the heat transfer through the roof. This section outlines the setup of an experiment that could accomplish this task. We recommend the construction of two sample chambers: one with a green roof as specified in Section 4.2.1.2, and one with a traditional roof as described in Section 4.2.1.1. An additional layer would be needed to provide structural support and simulate a 6” concrete slab. A material with a lower thickness and a higher thermal resistance per unit thickness than concrete would sufficiently simulate the thermal resistance of the slab. The walls and floor would be equipped with enough insulation such that the heat transfer through these layers is negligible compared to the heat transfer through the roof layer. The chambers would encompass approximately 25 square feet of roof area each, and the depth of the chambers should not be of concern. This is discussed in further detail for each of two alternative systems for measuring energy transfer.

In the first system, each chamber would be equipped with an independent air conditioning system and thermostat that would keep the interior air temperature at 70°F. The electricity used by the air conditioner would be measured for each system, and records could be used to determine the cost of energy used to maintain the interior temperatures for each roofing system. As long as thermostats are placed at the mid-height of the chamber, the depth of the chamber should be controlled only by what is required by air ducts and construction constraints. The only drawback of this setup would be obtaining an air conditioning system small enough to control such a small space. Electricity values may be thrown off by excessively frequent start-ups and shut-downs of the air conditioner. This model could be built for approximately $3000.00, have a low labor requirement, and have pretty good accuracy in measuring energy transfer.

Alternatively, one could use the same physical setup, but measure heat transfer by utilizing the melt-rate of ice blocks and knowledge of the heat of fusion of water. This would require the design of an ice supply and drainage system within the chamber that would not sacrifice the chambers’ thermal isolation. The amount of ice melted could be found by installing a permanent scale under each chamber and measuring the change in weight with time. If responsible experimental practices are used and data is recorded carefully, this model will very accurately measure the heat transfer through each roofing system. This model could be built for approximately $2000.00, would have excellent accuracy in measuring energy transfer, but would be relatively labor-intensive.

4.7.3 Future Marketing Plan

Individuals continuing our project to setup a market in Puerto Rico already have a substantial amount of contact information available in Appendix A and Appendix F. This information will help to start a very in-depth analysis of what we hope to become an expansive market in on the island. Each category aims at a different aspect of the market so referring back to our methodology section 3.4 we have outlined questions that will start off the initial thinking of ideas that can be offered to the three major sections. Using our contacts a much broader width of analysis can be completed and ideas and new problems can be brought forward. These problems will then have to be looked into for experimentation and solutions to help the market along. Overall the ideas that corporations express, which they will need to have happen before investment in green roofs, will be a great start to legislative motions. Hopefully with environmental groups in support, after large potential buyers and construction agencies have given their interest and capabilities to produce green roofs there will be opportunities for funding. This further investment in green roofs hopefully from both the government and environmental agencies will drive the costs of green roofs down making the market available to everyone, getting into the market of single unit houses which have already shown great interest in this concept. A continued marketing process can help to bring the knowledge and availability of green roofs to a level where it is an easily accessible option in everyday construction.

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6 Appendices

Appendix A Table of Contacts

Type of Contact	Name of Contact	Organization	Organization Description	Notes	Source	Contact Info.
Industry Insiders						
Construction Companies						
Architectural/ Engineering Firms	Alex Sepulveda			Mechanical engineer and Interested in the Subject	Beatriz Arsuaga	ajs62@cornell.edu
Architectural/ Engineering Firms	Nicolas Iturregui			landscaper and consultant	Beatriz Arsuaga	787-765-2083
Architectural/ Engineering Firms	Edith Calzadilla	CSA Group	project planning and design, including buildings, transportation, & environmental services.	Sponsor and WPI Friend, source contact	Beatriz Arsuaga	ecalzadilla@csagroup.com
Architectural/ Engineering Firms	Alexandra Teran	Environmental Resources Management	managing environmental and related risks.	Env. Mgt. Leader @ ERM	Beatriz Arsuaga	alex.teran@erm.com
Potential Customers						
Environmentally Conscious Organizations	Ms. Marla Ciares	Janssen	Pharmaceutical company	Env. Manager for WPI sponsor	Beatriz Arsuaga	mciares1@psgapr.jnj.com
Environmentally Conscious Organizations	Evet Vera	Baxter	expertise in medical devices, pharmaceuticals and biotechnology	env. Mgr., potential sponsor	Beatriz Arsuaga	evet_vera@baxter.com
Environmentally Conscious Organizations	Angel Alicia	Baxter	expertise in medical devices, pharmaceuticals and biotechnology	energy manager	Beatriz Arsuaga	angel_alicia@baxter.com
Environmentally Conscious Organizations	Mr. Jean S. López	Dynaco	Pharmaceutical company	Project Engineer		
Environmentally Conscious Land Developers	Raul Colon			Civil Engineer and Land Developer	Beatriz Arsuaga	raulcolon@yunque.net
Environmental Organizations						
Government Organization	Magaly Figueroa	US Dept. of Forestry			Beatriz Arsuaga	mafigueroa@fs.fed.us
Government Organization	Carlos Dominguez	US Dept. of Forestry			Beatriz Arsuaga	cdominguez@fs.fed.us
Energy Conservation Groups						
Groundwater Pollution Groups						
Air Pollution Groups						
Solid Waste	Mickey Ray			waste disposal consultant	Beatriz Arsuaga	theearthgroupinc@hotmail.com
EPA						
Informational Contacts						
Professor	Miquel A. Munoz	University of Puerto	Professor at the UPR agricultural experiment station	Researcher soil chemistry and mineralogy	Dr. Angel David Cruz	miquel_munoz@cca.uprm.edu
Professor	Dr. Angel David Cruz	University of Puerto	Department of Geography	Head of Project		tel-787-9230578
Professor	Eugeuio Santiago	University of Puerto	Department of Biology	Extensive knowledge in Plants	Dr. Angel David Cruz	tel-787-319-1903
Professor	Gloria Pico Acosta	University of Puerto	Professor at the UPR agricultural experiment station	Contact for other individuals with soil	Dr. Angel David Cruz	
Professor	Francisco Watlington	University of Puerto	Department of Geography	Provider of grapevines for experiment	Self	tel. 787-722-8754

Appendix B Watering Records

			Simulated Rain Schedule			
	Watering amount		Fertilizer*		Plant Food**	Observations
3/16/2005	6 buckets (3 gallon bucket)					
3/17/2005	5 min. A.M. (hose)					
3/18/2005	5 min. A.M./2 min. P.M. (hose)					
3/19/2005	none					
3/20/2005	none					
3/21/2005	5 min. A.M.					Two Plants becoming green again, very minimal
3/22/2005	5 min. A.M.					
3/23/2005	5 min. A.M.		Evenly spread across		3 gallon jug-evenly spread	
3/24/2005	none					
3/25/2005	none					
3/26/2005	none					
3/27/2005	none					
3/28/2005	5 min. A.M.					Trimmed off all dead plant tops and distributed seeds in hope of composting and generation of new plants.
3/29/2005	5 min. A.M.					More growth, possible weed and ferns
3/30/2005	5 min. A.M.					Potential plant growth in patches across most of the plot, grass and ferns
3/31/2005	5 min. A.M.					Growth expanding
4/1/2005	5 min. A.M.				3 gallon jug-evenly spread	
4/2/2005						
4/3/2005						
4/4/2005	5 min. A.M.					
4/5/2005	5 min. A.M.					
4/6/2005	5 min. A.M.					
4/7/2005	5 min. A.M.					Strike Started by students on Campus
4/8/2005	none					
4/9/2005	5 min. A.M.					Access limited due to strike, had to come in on Saturday. Growth increased to noticeable levels of green, Planted several spots of green vegetation,

4/10/2005	none					Strike Continues
4/11/2005	none					Strike Continues
4/12/2005	none					Strike Continues
4/13/2005	none					Strike Continues
4/14/2005	none					Strike Continues
4/15/2005	none					Strike Continues
4/16/2005	none					Strike Continues
4/17/2005	none					Strike Continues
4/18/2005	none					Strike Continues
4/19/2005	none					Strike Continues
4/20/2005	5 min A.M.					Access to school is given by President of school, return to campus
4/21/2005	none					Rainfall has been plentiful so no watering is needed
4/22/2005	none					Rooftop is thriving almost completely green
4/23/2005	none					Strike Continues
4/24/2005	none					Strike Continues
4/25/2005	none					Check Observational Guide for observations.
4/26/2005	none					Strike Continues
4/27/2005	none					Strike Continues
4/28/2005	none					Strike Continues
4/29/2005						
4/30/2005						
5/1/2005						
5/2/2005						
5/3/2005						
5/4/2005						
5/5/2005						

*Fertilizer-Terra-Growers Gold (Turf and Shrubs)

**Plant Food-Premium grade (all purpose)

Appendix C Locally Available Plants

Nurseries or suppliers of plants:

1 - Plantas Tropicales de Puerto Rico Inc.
2 - Jardin Selecto
3 - Panoramic Garden
4 - Vivero Fideicomiso de Conservacion de PR
5 - Vivero Jardin Botanico UPR
6 – Gramas Lindas Inc

Plant availability

Species for Extensive Roofs	1	2	3	4	5	6
Allamanda cathartica		**X**				
Aloe vera		**X**	**X**			
Aloe walmsley's Bronze			**X**			
Bougainvillea		**X**				
Cactaceas			**X**			
Carissa						
Crassula muscosa						
Delosperma kelaidis						
Delosperma cooperi						
Delosperma nubigenum						
Haworthia margaritifera			**X**			
Haworthia paradoxa			**X**			
Haworthia limifolia			**X**			
Ipomoea pes Caprae						
Kalanchoe		**X**	**X**			
Maleophora Luteola						
Maleophora Crocea						
Sedum mexicanum			**X**			
Sedum diffusum						
Sphagneticola trilobata		**X**	**X**			

(Quevedo, 2000)

Appendix D Observational Guide to Long Term Experiment

Green Roofs Observational Guide

Observer- ______________________________

Date- ______________________________

Time- ______________________________

Weekly Average Temperature (°C)- ______________________________

Weekly Average Rainfall (mm)- ______________________ **Watering-** __________

Photograph plots

	Experimental Plots			
6	Open for Future Development	Open for Future Development	Open for Future Development	Open for Future Development
5	Open for Future Development	*Haworthia limifolia* T.B.D. T.B.D.	Open for Future Development	Open for Future Development
4	*Haworthia limifolia* T.B.D. T.B.D.	*Haworthia limifolia* T.B.D. T.B.D.	Open for Future Development	Open for Future Development
3	T.B.D.	T.B.D.	*Allamanda catharica*	*Allamanda catharica*
2	*Kalanchoe blossfeldiana*	*Kalanchoe blossfeldiana*	T.B.D.	T.B.D.
1	T.B.D.	T.B.D.	*Kalanchoe*	*Kalanchoe*
	A	B	C	D

Visual Observations-(New growths, flowers, offspring, foliage color and decaying or dying leaves)

Measurement Observations-(Radial lengths, height, growth lengths, flower size and leaf size)

	Stem Circumference	Height	Radial Dimensions	Growth Lengths	Leaf Size
Limestone Plot-					

Comments-

Volcanic Plot-					

Comments-

Limestone Plot-					

Comments-

Volcanic Plot-					

Comments-

Initial Observational Sheet:

	Stem Circumference	Height	Radial Dimensions	Growth Lengths	Leaf Size
Limestone Plot- A1	.75	6 cm	37 cm EW 53 cm NS	22 cm	1 cm

Comments-

- Many flowers 2.5 cm in diameter
- Little growing near the base
- Unhealthy look

Volcanic Plot- B1	1 cm	3.5 cm	47 cm EW 57 cm NS	24 cm	1.5 cm

Comments-

- Many flowers 2.5 cm in diameter with green leaves
- Has spread a large amount
- Looks very healthy
- Great choice of plant and substrate

Limestone Plot- C1	0.5 cm	Green – 18 cm Brown- 8 cm	G-20 NS; 20 EW B-10 NS; 10 EW	G- 10 cm B-5 cm	G-7.5 x 3.5cm B- 5x1.5cm

Comments-

Kalanchoe

- Ground cover minimal, growth is vertical
- Green plant has larger leaves and grows taller
- Brown plant sprouts small buds off the tips of leaves.

Volcanic Plot- D1	0.5 cm	Green- 15cm Brown- 8cm	G- 16 NS; 16 EW B-10 NS; 10 EW	G- 11cm B- 5cm	G- 9x4cm B- 5x1cm

Comments-

Kalanchoe

- Several weeds growing in the middle of the plot
- Ground cover minimal, growth is vertical
- Green plant has larger leaves and grows taller
- Brown plant sprouts small buds off the tips of leaves.

	Stem Circumference	Height	Radial Dimensions	Growth Lengths	Leaf Size
Limestone Plot- A2	1.5 cm	16cm	10cm NS 10 cm EW	9 cm	5 x 3 cm

Comments-

Kalanchoe blossfeldiana

- Browning on base leaves
- Flowers discolored
- Several dead flowers

Volcanic Plot- B2	1.5 c	16cm	10 cm NS 10 cm EW	11 cm	7 x 4 cm

Comments-

Kalanchoe blossfeldiana

- Leaves very crisp and black, some still green
- Not many flowers left

Limestone Plot- C2	1.5 cm	18 cm	11 cm EW 8 cm NS	8 cm	6 x 6 cm

Comments-

- Leaves partially deteriorating
- Flowers doing well
- Several buds waiting to blossom, but six flowers are dead

Volcanic Plot- D2	1.5 cm	17 cm	12 cm NS 12 cm EW	9 cm	6 x 6 cm

Comments-

- Small amount of flowers
- Clusters of bud on top of the plant
- Several dead flowers
- Leaves are healthy

	Stem Circumference	**Height**	**Radial Dimensions**	**Growth Lengths**	**Leaf Size**
Limestone Plot- A3	0.2 cm	16 cm	14 cm EW 13 cm NS	16 cm	.1 x 1 cm

Comments-

- Very green
- Not growing much

Volcanic Plot- B3	.2	15 cm	15 cm EW 15 cm NW	15 cm	.1 x 1.5 cm

Comments-

- Very green and healthy

Limestone Plot- C3	2 cm	31 cm	20 cm EW 20 cm NS	26 cm	1 x 3 cm

Comments-

Allamanda catharica

- All starting leaves have fallen off
- New sprouts coming with green leaves
- Only one flower remains

Volcanic Plot- D3	2 cm	29 cm	36 cm EW 36 cm NS	28 cm	1.5 x 5 cm

Comments-

Allamanda catharica

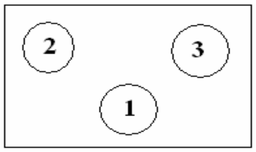
- Lost some leaves, but most maintained
- Three flowers 8 cm diameter,
- Several buds forming

	Stem Circumference	**Height**	**Radial Dimensions**	**Growth Lengths**	**Leaf Size**
Limestone Plot- A4	1) 0.5 cm 2) 0.5 cm 3) –	1) 10 cm 2) 9 cm 3) 7 cm	1) 10 NS; 7 EW 2) 10 NS; 14 EW 3) 10 NS; 9 EW	1) – 2) – 3) –	1) 3x1.5 cm 2) 2x5 cm 3) –

Comments-

1) TBD
2) TBD
3) *Haworthia Limofilia*

Diagram of Plot:



1)
- Leaves becoming brown, unhealthy look

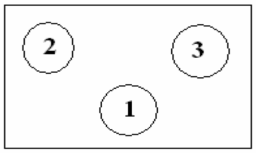
2)
- Looks good, still very green

3)
- Little plant is growing on side, but the leaves are turning brown at the bottom

Volcanic Plot- B4	1) 0.5 cm 2) 0.5 cm 3) –	1) 10 cm 2) 9cm 3) 7 cm	1) 10 NS; 8 EW 2) 10 NS; 13 EW 3) 8 NS; 14 EW	1) – 2) – 3) –	1) 2x4 cm 2) 2x5 cm 3) –

Comments-

1) TBD
2) TBD
3) *Haworthia Limofilia*



1)
- Leaves mostly green, some brown

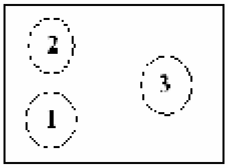
2)
- Leaves mostly green and healthy, one leaf discolored

3)
- Growing plant off side, leaves turning brown

Volcanic Plot- B5	1) .5 cm 2) .5 cm 3) –	1) 9 cm 2) 6 cm 3) 3 cm	1) 13 NS; 9 EW 2) 12 NS; 8 EW 3) 45 NS; 44 EW	1) – 2) – 3) 29 cm	1) 2x5 cm 2) – 3) .1x.1 cm

Comments:

1) TBD
2) Haworthia Limofilia
3) TBD



1)
- Leaves seem healthy

2)
- Many leaves discolored and unhealthy, still growing

3)
- Thriving, leaves are healthy with flowers and it is growing well

Appendix E Temperature Sensor Network User's Guide

UPR Green Roof Temperature Sensor Network

Introduction

The temperature sensor network created at the UPR Rio Piedras campus is designed to acquire temperature measurements at different points on the green roof at a fixed interval. This temperature data can then be used to evaluate the effectiveness of the green roof. There are three main components of the sensor network, the sensors, the data acquisition hardware, and the computer based software.

Sensors

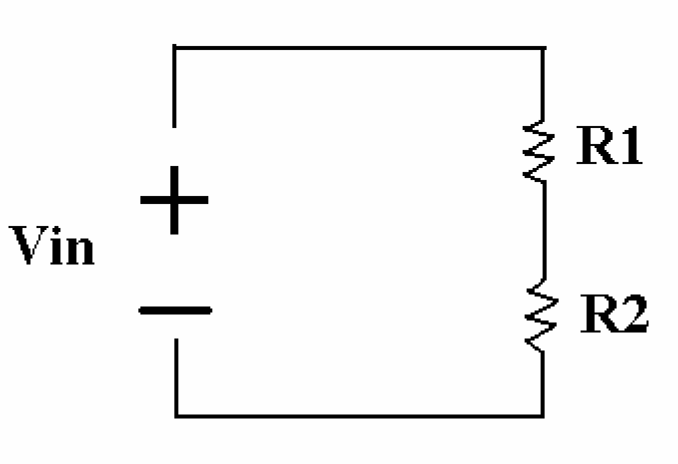
The temperatures on the roof are measured by Betatherm 5K3A1A thermistors. A thermistor is an electrical resistor whose resistance changes a significant amount with a change in temperature. The resistance-temperature relationship is given by the thermistor manufacturer. The resistance temperature chart for the betatherm resistor that was actually used is shown below in figure 1.

Temp	R Value	Temp	R Value	Temp	R Value
(°C)	(Ohms)	(°C)	(Ohms)	(°C)	(Ohms)
1	15,515.20	26	4,786.00	51	1,733.46
2	14,750.00	27	4,582.40	52	1,669.30
3	14,027.10	28	4,388.50	53	1,607.81
4	13,343.80	29	4,203.90	54	1,548.96
5	12,697.80	30	4,028.00	55	1,492.54
6	12,086.30	31	3,860.50	56	1,438.46
7	11,508.00	32	3,700.80	57	1,386.62
8	10,960.80	33	3,548.60	58	1,336.93
9	10,442.60	34	3,403.50	59	1,289.26
10	9,951.80	35	3,265.10	60	1,243.53
11	9,486.80	36	3,133.10	61	1,199.70
12	9,046.30	37	3,007.10	62	1,157.59
13	8,628.70	38	2,886.90	63	1,117.18
14	8,232.50	39	2,772.10	64	1,078.37
15	7,857.00	40	2,662.40	65	1,041.15
16	7,500.60	41	2,557.80	66	1,005.38
17	7,162.30	42	2,457.70	67	971.03
18	6,841.30	43	2,362.10	68	938.02
19	6,536.40	44	2,270.80	69	906.3
20	6,246.80	45	2,183.45	70	875.81
21	5,971.60	46	2,099.93		
22	5,710.00	47	2,020.04		
23	5,461.30	48	1,943.60		
24	5,225.00	49	1,870.50		
25	**5,000.00**	50	1,800.49		

Temperature Resistance chart for Betatherm 5K3A1A thermistor

To measure the resistance of the thermistor a voltage divider is utilized. A voltage divider consists of two resistors in series with a voltage applied. The voltage drop, or voltage measured across a resistor, can be calculated by the following equation:

$$V = V_{in} \times R_1 / (R_1 + R_2)$$



Principle of voltage drop

The sensors in the network are arranged so this relationship can be utilized. In the diagram above R1 is replaced by the thermistor and there is a lead wire attached right above and below R2 so the voltage drop can be read. These sensor setups are grouped in sets of four with common power supply wires and output voltage wires grouped together color coded to match the corresponding sensor. The power supply wires from each set of sensors are attached to a 3 volt transformer which is plugged into a normal wall outlet. The voltage out lead wires from each sensor as well as their common ground is connected to the data Acquisition hardware where it can be measured and manipulated.

Data Acquisition Hardware

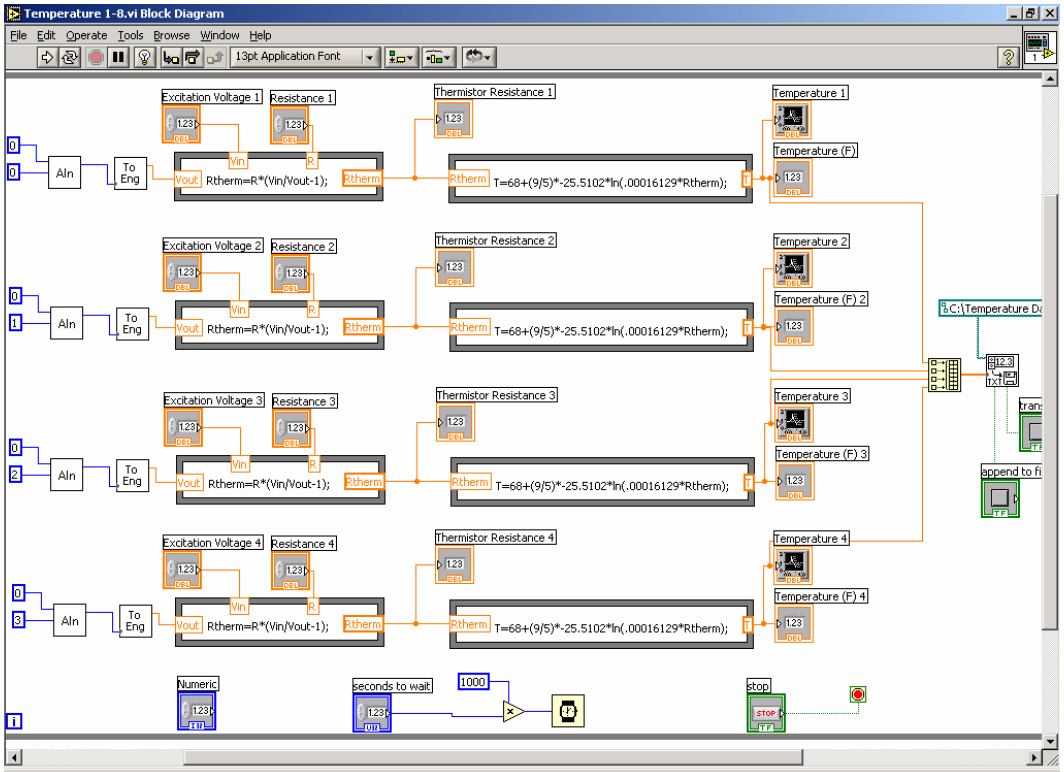
The purpose of the data acquisition hardware is to take the analog voltage output from the sensor network and convert it into a digital signal so that it can be manipulated by a computer. The units used in this network are Measurement Computing PMD 1208LS shown below.

PMD-1208LS Data Acquisition

The PMD-1208LS provides 8, 11 bit single ended analog inputs. Each of these channels has a range of -10V to +10V which means that the voltage can be read in .01V steps which equates to about 70° degree accuracy. The input voltage is converted into a digital signal by the PMD-1208LS and sent to the computer through the USB cable where it can be manipulated by the software to yield meaningful results.

Software

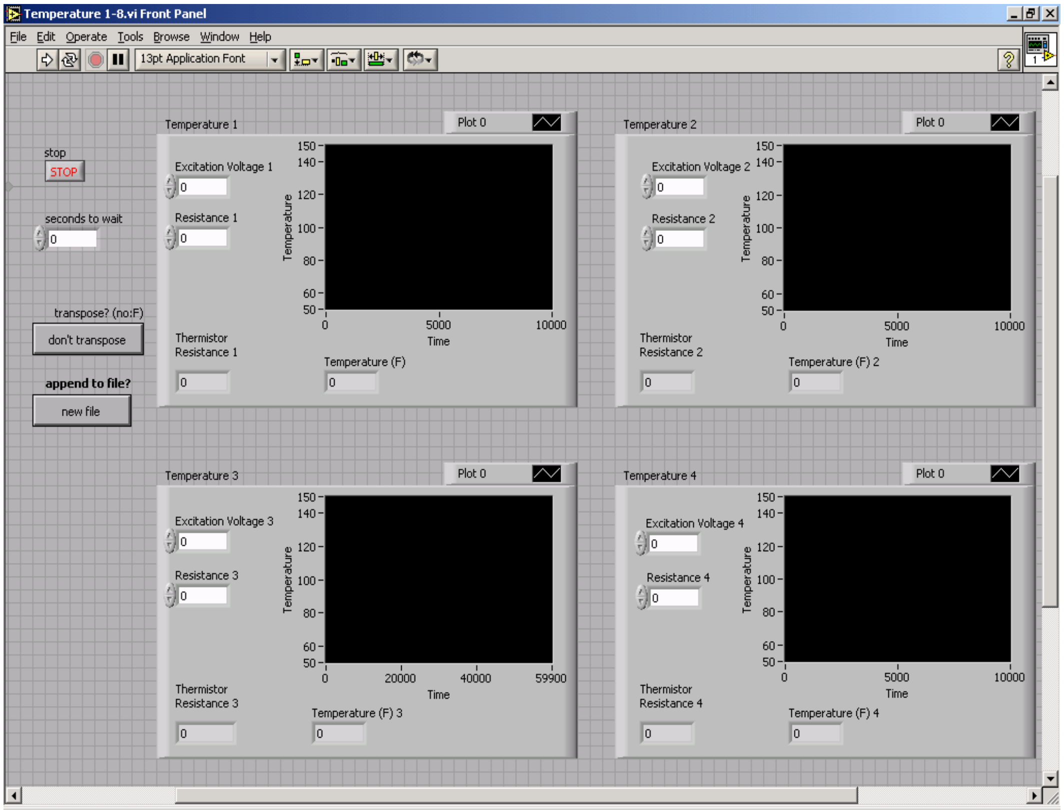
In any sensor network software is required to accept the raw data, convert it to useful information and display it in a way that is desirable by the end user. The National Instruments LabView software package is a very common package used by experimenters to create their own project specific software. For this network a Virtual Instrument was created in LabView 7.1 to perform the desired data manipulation and output. Using an equation derived from the voltage division principle as mentioned above the voltages read by the PMD-1208LS are converted into the resistance of the thermistor. Then, using the equation of a line fit to the temperature-resistance data shown above this resistance is changed into the temperature of the thermistor. These two main computational steps are performed by the two formula nodes, the two grey boxes on each line.



```
Rtherm=R*(Vin/Vout-1);
T=68+(9/5)*-25.5102*ln(.00016129*Rtherm);
```

Block diagram of VI

The bigger blue squares to the left of each line are the inputs from the hardware, the first accepts the digital input and the second converts the digital signal into the voltage read. The smaller blue boxes all the way to the left specify the board number and channel number of the input. The orange boxes represent numerical inputs or outputs shown on the front panel of the Virtual Instrument below. The boxes on the far right are the data output section of the Virtual Instrument. These group the temperatures into an array and output the array to an excel spreadsheet. The combination of the 4 boxes on the bottom controls the time between readings and can be adjusted on the front panel.



Front Panel of VI

Instructions for use

The following will provide a guide for using the temperature sensor network as it was arranged upon the completion of the WPI project. If any changes are to be made it is suggested that a thorough understanding of the entire setup be gained so that any modifications do not change the functionality of the network.

Hardware

The first step in using the temperature network is to confirm that all the hardware is in working condition. As the network was left everything should be connected properly and in its place, however there if anything is rearranged the user must take the following two steps to ensure proper operation. First the connections to the PMD-1208LS must be checked. The following chart provides the proper connections for all the lead wires from the network to the data acquisition hardware. The user must also make sure that the PMD-1208LS is connected properly to the computer with its USB cable.

Board 0	
Pin #	**Wire**
1	red 1
2	yellow 1
3	black 1
4	green 1
5	blue 1
6	
7	red 2
8	yellow 2
9	black 2
10	green 2
11	blue 2
12	

Board 1	
Pin #	**Wire**
1	red 3
2	yellow 3
3	black 3
4	green 3
5	blue 3
6	
7	red 4
8	yellow 4
9	black 4
10	green 4
11	blue 4
12	

Note: Pins 1,3,6,9,12 are all ground pins so the black wires (ground) can be connected to any of these pins

Chart showing correct wire connections

InstaCal

The next step in running the temperature sensor network is to open the PMD-1208LS configuration utility, InstaCal. Instacal should be on the computer desktop or can be found in Start >> Programs >> Measurement Computing >> InstaCal. Once InstaCal opens there should be two PMD-1208LS boards shown. They should be labeled board 0 and board 1. If one or neither of the boards are shown close InstaCal, check the PMD-1208LS USB connection to the computer and try opening InstaCal again. In InstaCal right click on each board and choose configure. In the configuration utility make sure the boards are set for 8 single ended inputs. By picking a board and selecting test >> AD test from the dropdown menu the user can check that each channel is receiving a signal and determine what the value of the signal is. Also by selecting a board and choosing calibrate the calibration utility will open. This utility should be run every six months or so to ensure accurate results. By following the onscreen instructions and using the special wires provided the calibration process should take no longer than ten minutes. There are also other functions of InstaCal that can be used, but are not required for the temperature network.

LabView

After competing the required operations in InstaCal, open Labview 7.1 from the desktop or Start >> Programs >> National Instruments >> Labview 7.1 >> Labview. On the first menu select continue to open the main menu. Select the Open drop down menu and click on Temperature Network.vi. After the Virtual Instrument opens it will be ready to run by clicking the run button ⇨ in the upper left hand corner of the screen. The values of the time delay in seconds can be changed by clicking in the box and typing in the desired value. To make the new value the default, select the Operate menu from the upper toolbar and choose Make Current Values Default. This should be done if a different sampling rate is desired every time the program is opened. While the program is running it will be constantly outputting the data it gathers to a spreadsheet file found at C:\TemperatureData\data.xls. This spreadsheet contains the date and time the samples were taken and the temperature data for each sensor as shown below.

Date	Time	Sensor	Sensor	Sensor	Sensor	Sensor	Sensor	Sensor	Sensor

		1	2	3	4	5	6	7	8
4.14	2.52	77.3	78.1	77.3	77.3	79.4	78.1	79.4	77.3
4.14	2.53	77.3	78.1	77.3	77.3	79.4	78.1	79.4	77.3
4.14	2.54	77.3	78.1	77.3	77.3	79.4	78.1	79.4	77.3
4.14	2.55	77.3	78.1	77.3	77.3	79.4	78.1	79.4	77.3
4.14	2.56	77.3	78.1	77.3	77.3	79.4	78.1	79.4	77.3
4.14	2.57	77.3	78.1	77.3	77.3	79.4	78.1	79.4	77.3
4.14	2.58	77.3	78.1	77.3	77.3	79.4	78.1	79.4	77.3
4.14	2.59	77.3	78.1	77.3	77.3	79.4	78.1	79.4	77.3
4.14	3	77.3	78.1	77.3	77.3	79.4	78.1	79.4	77.3
4.14	3.01	77.3	78.1	77.3	78.1	79.4	78.1	79.4	77.3
4.14	3.02	77.3	78.1	77.3	78.1	79.4	78.1	79.4	77.3
4.14	3.03	77.3	78.1	77.3	78.1	79.4	78.1	79.4	77.3
4.14	3.04	77.3	78.1	77.3	78.1	79.4	79.4	79.4	77.3
4.14	3.05	78.1	78.1	77.3	78.1	79.4	79.4	79.4	77.3
4.14	3.06	78.1	78.1	77.3	78.1	79.4	79.4	79.4	77.3
4.14	3.07	78.1	78.1	77.3	78.1	79.4	79.4	79.4	77.3
4.14	3.08	78.1	78.1	77.3	78.1	79.4	79.4	79.4	77.3
4.14	3.09	78.1	78.1	77.3	78.1	79.4	79.4	79.4	77.3
4.14	3.1	78.1	78.1	77.3	78.1	79.4	79.4	79.4	77.3
4.14	3.11	78.1	78.1	77.3	78.1	79.4	79.4	79.4	77.3
4.14	3.12	78.1	78.1	77.3	78.1	79.4	79.4	79.4	77.3
4.14	3.13	78.1	78.1	77.3	78.1	79.4	79.4	79.4	77.3
4.14	3.14	78.1	78.1	77.3	78.1	79.4	79.4	79.4	77.3
4.14	3.15	78.1	78.1	77.3	77.3	79.4	79.4	79.4	77.3
4.14	3.16	78.1	78.1	77.3	77.3	79.4	79.4	79.4	77.3

Example of the spreadsheet output

The program is set up to begin writing data on the first empty row, so it will write the data from different data recording sessions in the same spreadsheet. To avoid the spreadsheet can be saved as a different file name and then the original data.xls file deleted so that LabView will create a new file. This program can be run continuously although the amount of data that can be recorded in the spreadsheet will be limited at some point. The data in the spreadsheets can be easily used for many types of evaluation.

If you have any problems with this network contact Brian Miley, bmiley@wpi.edu
All manuals and software needed for the network will be provided to Prof. Ángel David Cruz of UPR.

Specifications
Hardware

PMD-1208LS USB-based Personal Measurement Device
    8 channel
    11 bits over a ±10 V Range
    5V USB supplied power

Betatherm Temperature Solutions 5K3A1A thermisors
    ±.25° C accuracy from 0 to 70° C
    1 second response time

Radioshack 271-1124 4.7K ohm resistor
    ½ Watt
    5% tolerance

Radioshack 278-862 Alarm Wire
    22 gauge

Software

National Instruments LabView 7.1
    Copyright 2004

Measurement Computing InstaCal 5.55

Measurement Computing Universal Library for LabView 7.10

Appendix F Green Roof Industry Contacts

Contact Name	Organization	Email Address	Notes
Kieran Townes	Bauder	k.townes@bauder.co.uk	Green roof pricing
Liz Thomas	Bauder	l.thomas@bauder.co.uk	Green roof materials
Sherry Uhlemann	Hydrotech USA	sguhlemann@aol.com	
Keith Ardron	ELT Green Roofs	keardron@rogers.com keith@eltgreenroofs.com	
Felix Romero	Danosa	fromero@danosapr.com	
Heidrun Eckert	Alumasc-ZinCo	heidrun.eckert@zinco.de	
Stuart Gaffin	Columbia University	sgaffin@rcn.com	Developing heat transfer model for green roof study at Pennsylvania State University

Appendix G Green Roof Installation Costs

Bauder Green Roof Estimatee,
10,000 SF

Item	Description	Low Price per SF	High Price per SF	Source	Location	Contact
Entire Assembly	Everything above structural support, planted via sod mats	$19.00	$21.00	Kieran Townes, Bauder	UK	Kieran Townes
Entire Assembly	Everything above structural support, seeded	$17.00	$19.00	Kieran Townes, Bauder	UK	Kieran Townes

Bauder Itemized, Contact Kieran Townes

		Material & Labor per SF	O&P per SF	Total	Estimated Labor Cost	Estimated Material Cost
Plants	X-Flor veg. blanket	$5.51	$0.55	$6.06	$1.20	$4.31
Growing Medium						
Filter Membrane						
Drainage						
Moisture Mat	SDF Mat	$1.32	$0.13	$1.45	$1.19	$0.13
Root Barrier	Plant-E	$2.28	$0.23	$2.51	$0.13	$2.15
Waterproofing Membrane	G4E Underlay	$1.93	$0.19	$2.12	$0.80	$1.13
Thermal Insulation	unlisted	$4.28	$0.43	$4.71	$0.20	$4.08
Vapor Control	x-pal	$1.49	$0.15	$1.64	$0.06	$1.43
Totals		$16.81	$1.68	**$18.49**		

ELT Green Roofs, Canada: Contact Keith Ardron			
Item	Description		Cost per SF
ELT Easy Green	Drainage/Moisture Layer		$4.00
Pregrown Vegetation Mat			$2.00
Root Barrier			$0.30
Irrigation			$1.00
Installation			$1.48
		Total	$8.78

Note: ELT estimate does not include insulation, waterproofing, vapor barrier

Hydrotech USA Materials Cost Breakdown , Contact Sherry Uhlemann

Item	**Packaging**	**Weight**	**Coverage**		**Price per SF**	**Price per Roll**
Garden Roof Components						
GARDENDRAIN GR15					$0.85	
FLORADRAIN FD25					$1.70	
FLORADRAIN FD40	Sheet	9	1m x 2m (21.52 SF)		$2.57	
FLORADRAIN FD60	Sheet	9	1m x 2m (21.52 SF)		$3.54	
MOISTURE MAT SSM45	Roll	111	2m x 50m (1,076 SF)		$0.80	
SYSTEM FILTER SF	Roll	49	2m x 100m (2,152 SF)		$0.40	
ROOT BARRIER WSF40	Roll	122	8m x 25m (2,152 SF)		$0.38	
HYDROFLEX RB (Root Barrier)	Roll	105	(.160” x 39.4” x 33.4) (109.6 SF)		$1.58	
Protection and Separation Layer						
HYDROFLEX 10	Roll	85	(.047” x 39.37” x 100.5’) (329 SF)	25 rolls/skid		$46.95
HYDROFLEX 30	Roll	90	(.090” x 39.37” x 50.25’) (164 SF)	25 rolls/skid		$54.12
HYDROFLEX 30	Roll	100	(.090” x 39.4” x 66) (216 SF)	20 rolls/skid		$71.28
HYDROFLEX RB	Roll	105	(.160” x 39.4” x 33.4’)(109.6 SF)		$1.58	
HYDROCAP 90 (Fire rated)	Roll	90	(.090” x 39.76” x 33.5”)(110 SF)	(25 Roll/Skid)		$79.00
HYDROCAP 160 (Fire rated)	Roll	110	(.160” x 39.76” x 33.5’) (Must order in skid quantity)	(25 Roll/Skid)		$99.90
PERMABOARD (3mil.)	Sheet	18	(.125” x 39.4” x 78.7”)	21.5 SF/Sheet	$0.33	
THERMABOARD (4.5 mil.)	Sheet	24		21.5 SF/Sheet	$0.48	

Appendix H Heat Transfer Model

Daily Energy Costs for Traditional Roof

Heat Transfer Analysis: Traditional Roof, No Cloud Cover

Reading ID Number		Date		**Energy Expended (kWh)**	**119.65**	**Cost ($)**	**$16.61**

Notes: This model is an assumption for traditional roofs on a sunny day. It assumes the indoor air temperature is maintained 24 hours per day at 70 degrees Fahrenheit.

*Step 1: Enter k-values in watts/meter*K*

Step 2: Enter thickness of respective layers in feet

Layer 1	
Name	Structural Concrete
K-Value	1.05
Thickness (ft.)	0.5
Thickness (m.)	0.1524
t/k	0.145142857

Layer 2	
Name	Insulation
K-Value	0.04
Thickness (ft.)	0.1
Thickness (m.)	0.03048
t/k	0.762

Layer 3	
Name	Waterproofing
K-Value	1.15
Thickness (ft.)	0.05
Thickness (m.)	0.01524
t/k	0.01325217

Summation of t/k	0.920395031

Step 3: Enter Roof Area, EER, and Energy Cost

	Square Feet	Square Meters
Roof Area	10000	929.0304
EER AC	15	
Cost of Electricity (cents per kWh)	13.886	

Step 3: Enter external and internal temperatures

Time	Exterior Surface Temperature (Fahrenheit)	Interior Surface Temperature (Fahrenheit)	Exterior Surface Temperature (Celsius)	Interior Surface Temperature (Celsius)	Temperature Difference (Celsius)	Q rate through roof (kWh per square meter per hour)	Total Q for given hour (kWh)	Total Q for given hour (BTU)	Q paid for (kWh)	Summation of Daily Energy Expenditure	Energy Cost for the day ($)
100	80	70	26.67	21.11	5.6	0.006	5.60767912	19134.19998	1.2756133	119.652	$16.61
200	80	70	26.67	21.11	5.6	0.006	5.60767912	19134.19998	1.2756133		
300	81	70	27.22	21.11	6.1	0.007	6.16844703	21047.61998	1.4031747		
400	80	70	26.67	21.11	5.6	0.006	5.60767912	19134.19998	1.2756133		
500	80	70	26.67	21.11	5.6	0.006	5.60767912	19134.19998	1.2756133		
600	81	70	27.22	21.11	6.1	0.007	6.16844703	21047.61998	1.4031747		
700	96	70	35.56	21.11	14.4	0.016	14.5799657	49748.91995	3.3165947		
800	107	70	41.67	21.11	20.6	0.022	20.7484128	70796.53993	4.7197693		
900	123	70	50.56	21.11	29.4	0.032	29.7206993	101411.2599	6.7607507		
1000	134	70	56.67	21.11	35.6	0.039	35.8891464	122458.8799	8.1639253		
1100	137	70	58.33	21.11	37.2	0.040	37.5714501	128199.1399	8.5466093		
1200	137	70	58.33	21.11	37.2	0.040	37.5714501	128199.1399	8.5466093		
1300	136	70	57.78	21.11	36.7	0.040	37.0106822	126285.7199	8.419048		
1400	137	70	58.33	21.11	37.2	0.040	37.5714501	128199.1399	8.5466093		
1500	137	70	58.33	21.11	37.2	0.040	37.5714501	128199.1399	8.5466093		
1600	136	70	57.78	21.11	36.7	0.040	37.0106822	126285.7199	8.419048		
1700	138	70	58.89	21.11	37.8	0.041	38.132218	130112.5599	8.6741707		
1800	136	70	57.78	21.11	36.7	0.040	37.0106822	126285.7199	8.419048		
1900	133	70	56.11	21.11	35.0	0.038	35.3283785	120545.4599	8.036364		
2000	107	70	41.67	21.11	20.6	0.022	20.7484128	70796.53993	4.7197693		
2100	91	70	32.78	21.11	11.7	0.013	11.7761262	40181.81996	2.678788		
2200	87	70	30.56	21.11	9.4	0.010	9.53305451	32528.13997	2.1685427		
2300	83	70	28.33	21.11	7.2	0.008	7.28998286	24874.45997	1.6582973		
2400	81	70	27.22	21.11	6.1	0.007	6.16844703	21047.61998	1.4031747		

Heat Transfer Analysis: Traditional Roof, 100% Cloud Cover

Reading ID Number		Date		**Energy Expended (kWh)**	**78.20**	**Cost ($)**	**$10.86**

Notes: This model is an assumption for traditional roofs on a cloudy day. It assumes the indoor air temperature is maintained 24 hours per day at 70 degrees Fahrenheit.

*Step 1: Enter k-values in watts/meter*K*

Step 2: Enter thickness of respective layers in feet

Layer 1	
Name	Structural Concrete
K-Value	1.05
Thickness (ft.)	0.5
Thickness (m.)	0.1524
t/k	0.145142857

Layer 2	
Name	Insulation
K-Value	0.04
Thickness (ft.)	0.1
Thickness (m.)	0.03048
t/k	0.762

Layer 3	
Name	Waterproofing
K-Value	1.15
Thickness (ft.)	0.05
Thickness (m.)	0.01524
t/k	0.01325217

Summation of t/k	0.920395031

Step 3: Enter Roof Area, EER, and Energy Cost

	Square Feet	Square Meters
Roof Area	10000	929.0304
EER AC	15	
Cost of Electricity (cents per kWh)	13.886	

Step 3: Enter external and internal temperatures

Time	**Exterior Surface Temperature (Fahrenheit)**	**Interior Surface Temperature (Fahrenheit)**	**Exterior Surface Temperature (Celsius)**	**Interior Surface Temperature (Celsius)**	**Temperature Difference (Celsius)**	**Q rate through roof (kWh per square meter per hour)**	**Total Q for given hour (kWh)**	**Total Q for given hour (BTU)**	**Q paid for (kWh)**	**Summation of Daily Energy Expenditure**	**Energy Cost for the day ($)**
100	80	70	26.67	21.11	5.6	0.006	5.60767912	19134.19998	1.2756133	78.1950	$10.86
200	80	70	26.67	21.11	5.6	0.006	5.60767912	19134.19998	1.2756133		
300	81	70	27.22	21.11	6.1	0.007	6.16844703	21047.61998	1.4031747		
400	80	70	26.67	21.11	5.6	0.006	5.60767912	19134.19998	1.2756133		
500	80	70	26.67	21.11	5.6	0.006	5.60767912	19134.19998	1.2756133		
600	81	70	27.22	21.11	6.1	0.007	6.16844703	21047.61998	1.4031747		
700	86	70	30.00	21.11	8.9	0.010	8.9722866	30614.71997	2.0409813		
800	95	70	35.00	21.11	13.9	0.015	14.0191978	47835.49995	3.1890333		
900	99	70	37.22	21.11	16.1	0.018	16.2622695	55489.17994	3.6992787		
1000	105	70	40.56	21.11	19.4	0.021	19.6268769	66969.69993	4.4646467		
1100	108	70	42.22	21.11	21.1	0.023	21.3091807	72709.95992	4.8473307		
1200	110	70	43.33	21.11	22.2	0.024	22.4307165	76536.79992	5.1024533		
1300	112	70	44.44	21.11	23.3	0.025	23.5522523	80363.63992	5.357576		
1400	112	70	44.44	21.11	23.3	0.025	23.5522523	80363.63992	5.357576		
1500	112	70	44.44	21.11	23.3	0.025	23.5522523	80363.63992	5.357576		
1600	112	70	44.44	21.11	23.3	0.025	23.5522523	80363.63992	5.357576		
1700	112	70	44.44	21.11	23.3	0.025	23.5522523	80363.63992	5.357576		
1800	105	70	40.56	21.11	19.4	0.021	19.6268769	66969.69993	4.4646467		
1900	100	70	37.78	21.11	16.7	0.018	16.8230374	57402.59994	3.82684		
2000	97	70	36.11	21.11	15.0	0.016	15.1407336	51662.33995	3.444156		
2100	93	70	33.89	21.11	12.8	0.014	12.897662	44008.65995	2.9339107		
2200	89	70	31.67	21.11	10.6	0.011	10.6545903	36354.97996	2.4236653		
2300	83	70	28.33	21.11	7.2	0.008	7.28998286	24874.45997	1.6582973		
2400	81	70	27.22	21.11	6.1	0.007	6.16844703	21047.61998	1.4031747		

Daily Energy Costs for Green Roof

Heat Transfer Analysis: Green Roof, No Cloud Cover

Reading ID Number		Date	4/8/2005	**Energy Expended (kWh)**	**47.96**	**Cost ($)**	**$6.66**

Notes: This model is an assumption for green roofs on a sunny day. It assumes the indoor air temperature is maintained 24 hours per day at 70 degrees Fahrenheit.

*Step 1: Enter k-values in watts/meter*K*

Step 2: Enter thickness of respective layers in feet

Layer 1	
Name	Structural Concrete
K-Value	1.05
Thickness (ft.)	0.5
Thickness (m.)	0.1524
t/k	0.145142857

Layer 2	
Name	Insulation
K-Value	0.04
Thickness (ft.)	0.1
Thickness (m.)	0.03048
t/k	0.762

Layer 3	
Name	Waterproofing
K-Value	1.15
Thickness (ft.)	0.05
Thickness (m.)	0.01524
t/k	0.01325217

Summation of t/k	0.920395031

Step 3: Enter Roof Area, EER, and Energy Cost

	Square Feet	Square Meters
Roof Area	10000	929.0304
EER AC	15	
Cost of Electricity (cents per kWh)	13.886	

Step 3: Enter external and internal temperatures

Time	**Exterior Surface Temperature (Fahrenheit)**	**Interior Surface Temperature (Fahrenheit)**	**Exterior Surface Temperature (Celsius)**	**Interior Surface Temperature (Celsius)**	**Temperature Difference (Celsius)**	**Q rate through roof (kWh per square meter per hour)**	**Total Q for given hour (kWh)**	**Total Q for given hour (BTU)**	**Q paid for (kWh)**	**Summation of Daily Energy Expenditure**	**Energy Cost for the day ($)**
100	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736	47.96306128	$6.66
200	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		
300	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		
400	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		
500	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		
600	83	70	28.33	21.11	7.2	0.008	7.28998286	24874.46	1.658297		
700	83	70	28.33	21.11	7.2	0.008	7.28998286	24874.46	1.658297		
800	84	70	28.89	21.11	7.8	0.008	7.85075077	26787.88	1.785859		
900	85	70	29.44	21.11	8.3	0.009	8.41151868	28701.3	1.91342		
1000	86	70	30.00	21.11	8.9	0.010	8.9722866	30614.72	2.040981		
1100	88	70	31.11	21.11	10.0	0.011	10.0938224	34441.56	2.296104		
1200	90	70	32.22	21.11	11.1	0.012	11.2153582	38268.4	2.551227		
1300	91	70	32.78	21.11	11.7	0.013	11.7761262	40181.82	2.678788		
1400	91	70	32.78	21.11	11.7	0.013	11.7761262	40181.82	2.678788		
1500	91	70	32.78	21.11	11.7	0.013	11.7761262	40181.82	2.678788		
1600	90	70	32.22	21.11	11.1	0.012	11.2153582	38268.4	2.551227		
1700	89	70	31.67	21.11	10.6	0.011	10.6545903	36354.98	2.423665		
1800	88	70	31.11	21.11	10.0	0.011	10.0938224	34441.56	2.296104		
1900	87	70	30.56	21.11	9.4	0.010	9.53305451	32528.14	2.168543		
2000	86	70	30.00	21.11	8.9	0.010	8.9722866	30614.72	2.040981		
2100	85	70	29.44	21.11	8.3	0.009	8.41151868	28701.3	1.91342		
2200	84	70	28.89	21.11	7.8	0.008	7.85075077	26787.88	1.785859		
2300	83	70	28.33	21.11	7.2	0.008	7.28998286	24874.46	1.658297		
2400	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		

Heat Transfer Analysis: Green Roof, 100% Cloud Cover

Reading ID Number		Date	4/8/2005	**Energy Expended (kWh)**	**42.22**	**Cost ($)**	**$5.86**

Notes: This model is an assumption for green roofs on a cloudy day. It assumes the indoor air temperature is maintained 24 hours per day at 70 degrees Fahrenheit.

*Step 1: Enter k-values in watts/meter*K*

Step 2: Enter thickness of respective layers in feet

Layer 1	
Name	Structural Concrete
K-Value	1.05
Thickness (ft.)	0.5
Thickness (m.)	0.1524
t/k	0.145142857

Layer 2	
Name	Insulation
K-Value	0.04
Thickness (ft.)	0.1
Thickness (m.)	0.03048
t/k	0.762

Layer 3	
Name	Waterproofing
K-Value	1.15
Thickness (ft.)	0.05
Thickness (m.)	0.01524
t/k	0.01325217

Summation of t/k	0.920395031

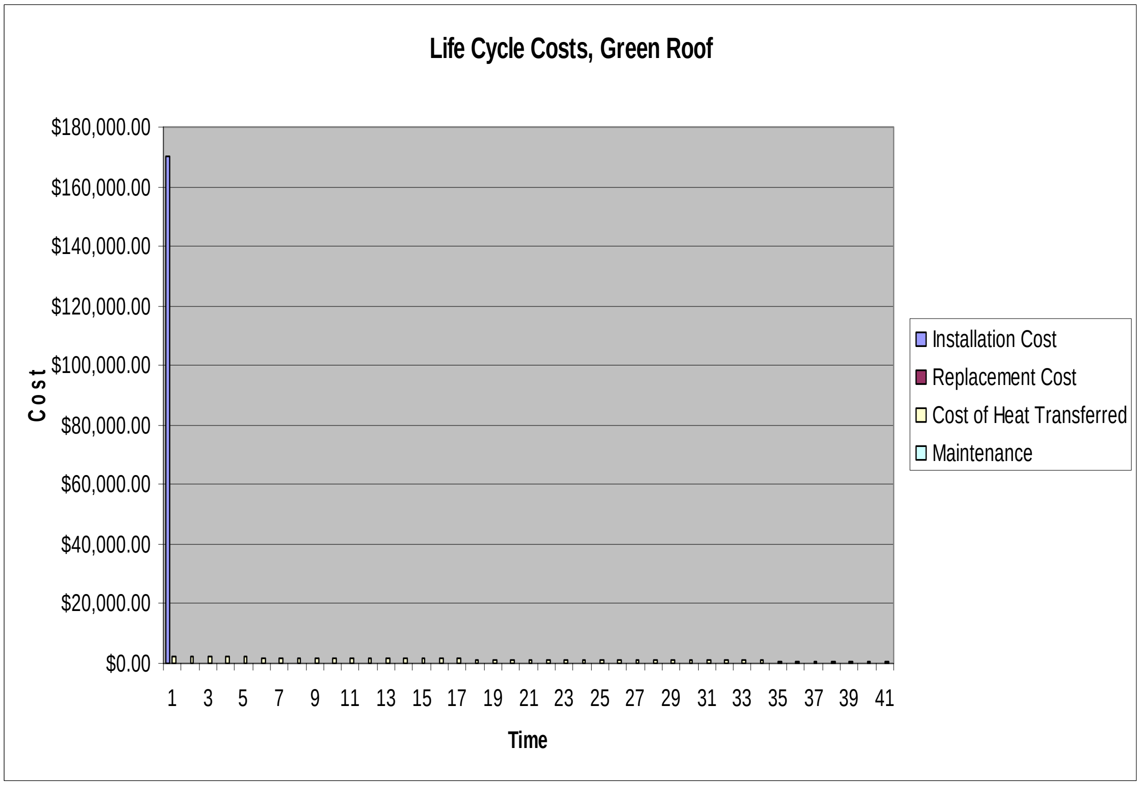
Step 3: Enter Roof Area, EER, and Energy Cost

	Square Feet	Square Meters
Roof Area	10000	929.0304
EER AC	15	
Cost of Electricity (cents per kWh)	13.886	

Step 3: Enter external and internal temperatures

Time	**Exterior Surface Temperature (Fahrenheit)**	**Interior Surface Temperature (Fahrenheit)**	**Exterior Surface Temperature (Celsius)**	**Interior Surface Temperature (Celsius)**	**Temperature Difference (Celsius)**	**Q rate through roof (kWh per square meter per hour)**	**Total Q for given hour (kWh)**	**Total Q for given hour (BTU)**	**Q paid for (kWh)**	**Summation of Daily Energy Expenditure**	**Energy Cost for the day ($)**
100	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736	42.22280129	$5.86
200	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		
300	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		
400	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		
500	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		
600	83	70	28.33	21.11	7.2	0.008	7.28998286	24874.46	1.658297		
700	83	70	28.33	21.11	7.2	0.008	7.28998286	24874.46	1.658297		
800	84	70	28.89	21.11	7.8	0.008	7.85075077	26787.88	1.785859		
900	84	70	28.89	21.11	7.8	0.008	7.85075077	26787.88	1.785859		
1000	85	70	29.44	21.11	8.3	0.009	8.41151868	28701.3	1.91342		
1100	85	70	29.44	21.11	8.3	0.009	8.41151868	28701.3	1.91342		
1200	85	70	29.44	21.11	8.3	0.009	8.41151868	28701.3	1.91342		
1300	86	70	30.00	21.11	8.9	0.010	8.9722866	30614.72	2.040981		
1400	86	70	30.00	21.11	8.9	0.010	8.9722866	30614.72	2.040981		
1500	86	70	30.00	21.11	8.9	0.010	8.9722866	30614.72	2.040981		
1600	86	70	30.00	21.11	8.9	0.010	8.9722866	30614.72	2.040981		
1700	85	70	29.44	21.11	8.3	0.009	8.41151868	28701.3	1.91342		
1800	85	70	29.44	21.11	8.3	0.009	8.41151868	28701.3	1.91342		
1900	84	70	28.89	21.11	7.8	0.008	7.85075077	26787.88	1.785859		
2000	84	70	28.89	21.11	7.8	0.008	7.85075077	26787.88	1.785859		
2100	83	70	28.33	21.11	7.2	0.008	7.28998286	24874.46	1.658297		
2200	83	70	28.33	21.11	7.2	0.008	7.28998286	24874.46	1.658297		
2300	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		
2400	82	70	27.78	21.11	6.7	0.007	6.72921495	22961.04	1.530736		

Appendix I Life-Cycle Cost Analysis



Life-Cycle Cost Analysis for Green Roof

Grand Total Time-Adjusted 40 Year Cost: **$252,092.80** **Cost per Square Foot:** **$25.21**

Notes: This model utilizes estimated installation, repair and replacement, and energy costs associated with green rooftop construction in order to determine all costs associated with the roof over its lifetime.

Input the roof area in square feet

Square Feet of Roof	10,000

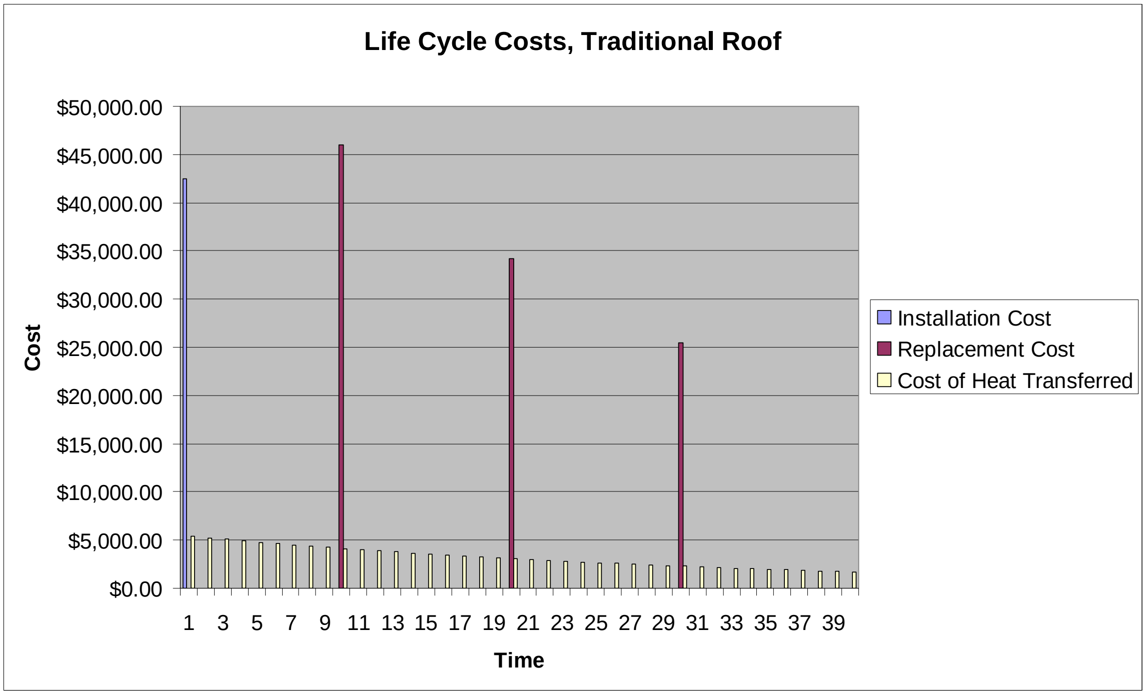
Input the expected inflation rate

Inflation Rate	0.03

Input from Green Roof Information

Type of Cost	**Source**	**Description**	**Frequency**	**Cost per Square Foot**	**Cost for this roof**
Installation	San Juan Green Roof Cost (Sheet 5)	See Worksheet 5	one time	$17.04	$170,428.50
Repair & Replacement				$0.00	$0.00
Energy Cost	Heat Transfer Worksheet	See Worksheet 7	annual	$0.23	$2,342.55
Annual Maintenance	RSMeans, ZinCo	2 days per 10000 SF	annual	$0.02	200
Increased Structural Cost	RSMeans	See	one time	$2.04	$20,351.33

Year	Installation Cost	Replacement Cost	Cost of Heat Transferred	Maintenance	Increased Structural Cost	Total Cost for the Year	Cumulative Cost	Cumulative Cost per Square Foot
0	$170,428.50		$2,342.55	$200.00	$20,351.33	$193,322.38	$193,322.38	$19.33
1			$2,274.32	$194.17		$2,468.49	$195,790.87	$19.58
2			$2,208.08	$188.52		$2,396.60	$198,187.47	$19.82
3			$2,143.76	$183.03		$2,326.79	$200,514.26	$20.05
4			$2,081.32	$177.70		$2,259.02	$202,773.28	$20.28
5			$2,020.70	$172.52		$2,193.22	$204,966.51	$20.50
6			$1,961.85	$167.50		$2,129.34	$207,095.85	$20.71
7			$1,904.71	$162.62		$2,067.32	$209,163.17	$20.92
8			$1,849.23	$157.88		$2,007.11	$211,170.29	$21.12
9			$1,795.37	$153.28		$1,948.65	$213,118.94	$21.31
10			$1,743.08	$148.82		$1,891.89	$215,010.83	$21.50
11			$1,692.31	$144.48		$1,836.79	$216,847.62	$21.68
12			$1,643.02	$140.28		$1,783.29	$218,630.91	$21.86
13			$1,595.16	$136.19		$1,731.35	$220,362.27	$22.04
14			$1,548.70	$132.22		$1,680.92	$222,043.19	$22.20
15			$1,503.59	$128.37		$1,631.96	$223,675.15	$22.37
16			$1,459.80	$124.63		$1,584.43	$225,259.59	$22.53
17			$1,417.28	$121.00		$1,538.28	$226,797.87	$22.68
18			$1,376.00	$117.48		$1,493.48	$228,291.35	$22.83
19			$1,335.92	$114.06		$1,449.98	$229,741.33	$22.97
20			$1,297.01	$110.74		$1,407.75	$231,149.08	$23.11
21			$1,259.23	$107.51		$1,366.74	$232,515.82	$23.25
22			$1,222.56	$104.38		$1,326.94	$233,842.76	$23.38
23			$1,186.95	$101.34		$1,288.29	$235,131.04	$23.51
24			$1,152.38	$98.39		$1,250.77	$236,381.81	$23.64
25			$1,118.81	$95.52		$1,214.34	$237,596.14	$23.76
26			$1,086.23	$92.74		$1,178.97	$238,775.11	$23.88
27			$1,054.59	$90.04		$1,144.63	$239,919.74	$23.99
28			$1,023.87	$87.42		$1,111.29	$241,031.03	$24.10
29			$994.05	$84.87		$1,078.92	$242,109.95	$24.21
30			$965.10	$82.40		$1,047.50	$243,157.44	$24.32
31			$936.99	$80.00		$1,016.99	$244,174.43	$24.42
32			$909.70	$77.67		$987.37	$245,161.80	$24.52
33			$883.20	$75.41		$958.61	$246,120.40	$24.61
34			$857.48	$73.21		$930.69	$247,051.09	$24.71
35			$832.50	$71.08		$903.58	$247,954.67	$24.80
36			$808.26	$69.01		$877.26	$248,831.93	$24.88
37			$784.71	$67.00		$851.71	$249,683.64	$24.97
38			$761.86	$65.05		$826.90	$250,510.54	$25.05
39			$739.67	$63.15		$802.82	$251,313.36	$25.13
40			$718.12	$61.31		$779.44	$252,092.80	$25.21
Total	$170,428.50	$0.00	$56,490.01	$4,822.95	$20,351.33			
Grand Total						$252,092.80		
Grand Total per Square Foot						$25.21		


Life Cycle Costs, Traditional Roof
Cost
$50,000.00
$45,000.00
$40,000.00
$35,000.00
$30,000.00
$25,000.00
$20,000.00
$15,000.00
$10,000.00
$5,000.00
$0.00
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39
Time
Installation Cost
Replacement Cost
Cost of Heat Transferred

Life-Cycle Cost Analysis for Traditional Roof

Grand Total Time-Adjusted 40 Year Cost: $277,793.93 Cost per Square Foot: $27.78

Notes: This model utilizes estimated installation, repair and replacement, and energy costs associated with traditional rooftop construction in order to determine all costs associated with the roof over its lifetime.

Input the roof area in square feet

Square Feet of Roof	10,000

Input the expected inflation rate

Inflation Rate	0.03

Input from Traditional Roof Installation Costs per square foot, Modified Bitumen

Type of Cost	**Source**	**Description**	**Frequency**	**Cost per Square Foot**	**Cost for this roof**
Installation	D Waterproofing (Worksheet 3)	See Worksheet 3	one time	$4.25	$42,500.00
Repair & Replacement	UPR Records (Worksheet 4)	See Worksheet 4	10 year interval	$6.00	$60,000.00
Energy Cost	Heat Transfer Worksheet	See Worksheet 6	annual	$0.54	$5,375.58

Year	Installation Cost	Replacement Cost	Cost of Heat Transferred	Total Cost for the Year	Cumulative Cost	Cumulative Cost per Square Foot
0	$42,500.00		$5,375.58	$47,875.58	$47,875.58	$4.79
1			$5,219.01	$5,219.01	$53,094.60	$5.31
2			$5,067.00	$5,067.00	$58,161.60	$5.82
3			$4,919.42	$4,919.42	$63,081.02	$6.31
4			$4,776.14	$4,776.14	$67,857.16	$6.79
5			$4,637.03	$4,637.03	$72,494.18	$7.25
6			$4,501.97	$4,501.97	$76,996.15	$7.70
7			$4,370.84	$4,370.84	$81,366.99	$8.14
8			$4,243.54	$4,243.54	$85,610.53	$8.56
9		$45,985.00	$4,119.94	$50,104.94	$135,715.47	$13.57
10			$3,999.94	$3,999.94	$139,715.41	$13.97
11			$3,883.44	$3,883.44	$143,598.85	$14.36
12			$3,770.33	$3,770.33	$147,369.17	$14.74
13			$3,660.51	$3,660.51	$151,029.68	$15.10
14			$3,553.89	$3,553.89	$154,583.58	$15.46
15			$3,450.38	$3,450.38	$158,033.96	$15.80
16			$3,349.89	$3,349.89	$161,383.85	$16.14
17			$3,252.32	$3,252.32	$164,636.16	$16.46
18			$3,157.59	$3,157.59	$167,793.75	$16.78
19		$34,217.16	$3,065.62	$37,282.78	$205,076.53	$20.51
20			$2,976.33	$2,976.33	$208,052.87	$20.81
21			$2,889.64	$2,889.64	$210,942.51	$21.09
22			$2,805.48	$2,805.48	$213,747.98	$21.37
23			$2,723.76	$2,723.76	$216,471.75	$21.65
24			$2,644.43	$2,644.43	$219,116.18	$21.91
25			$2,567.41	$2,567.41	$221,683.59	$22.17
26			$2,492.63	$2,492.63	$224,176.22	$22.42
27			$2,420.03	$2,420.03	$226,596.25	$22.66
28			$2,349.54	$2,349.54	$228,945.79	$22.89
29		$25,460.78	$2,281.11	$27,741.89	$256,687.68	$25.67
30			$2,214.67	$2,214.67	$258,902.35	$25.89
31			$2,150.16	$2,150.16	$261,052.51	$26.11
32			$2,087.54	$2,087.54	$263,140.05	$26.31
33			$2,026.74	$2,026.74	$265,166.79	$26.52
34			$1,967.71	$1,967.71	$267,134.49	$26.71
35			$1,910.39	$1,910.39	$269,044.89	$26.90
36			$1,854.75	$1,854.75	$270,899.64	$27.09
37			$1,800.73	$1,800.73	$272,700.37	$27.27
38			$1,748.28	$1,748.28	$274,448.65	$27.44
39			$1,697.36	$1,697.36	$276,146.01	$27.61
40			$1,647.92	$1,647.92	$277,793.93	$27.78
Total	$42,500.00	$105,662.95	$129,630.98			
Grand Total				$277,793.93		
Grand Total per Square Foot				$27.78		

Appendix J Macro Analysis- 1996 Rainfall Data

(National Oceanic and Atmospheric Administration)

Aug-96

Time

Date	12-1 AM	1-2 AM	2-3 AM	3-4 AM	4-5 AM	5-6 AM	6-7 AM	7-8 AM	8-9 AM	9-10 AM	10-11 AM	11-12 AM	12-1 PM	1-2 PM	2-3 PM	3-4 PM	4-5 PM	5-6 PM	6-7 PM	7-8 PM	8-9 PM	9-10 PM	10-11 PM	11-12 PM	Daily Total
1																	0.02							0.04	0.06
2	0.05	0.12																							0.17
3			0.03			0.06			0.12		0.32									0.02					0.55
4			0.07	0.03																					0.1
9			0.05							0.02															0.07
11																				0.03	0.45				0.48
13									0.05												0.03				0.08
14		0.02	0.08				0.03		0.42					0.35	0.03	0.68		0.03	0.02	0.09	0.07	0.05			1.87
15													0.08	0.11	0.1	0.09	0.08	0.09	0.07	0.03	0.02				0.67
16																0.03								0.04	0.07
17																	0.03	0.17							0.2
18																				0.11		0.02	0.02		0.15
23																			0.04	0.03					0.07
24				0.08					0.02																0.1
25																						0.02			0.02
26			0.03																						0.03
28																0.05	0.17			0.38	0.66				1.26
31	0.12																								0.12

Month Total 6.07

Sep-96

Time

Date	12-1 AM	1-2 AM	2-3 AM	3-4 AM	4-5 AM	5-6 AM	6-7 AM	7-8 AM	8-9 AM	9-10 AM	10-11 AM	11-12 AM	12-1 PM	1-2 PM	2-3 PM	3-4 PM	4-5 PM	5-6 PM	6-7 PM	7-8 PM	8-9 PM	9-10 PM	10-11 PM	11-12 PM	Daily Total
4																		0.22							0.22
5																0.11		0.08	0.08						0.27
7																			0.02		0.02				0.04
8		0.03			0.14																				0.17
9										0.17	0.02						0.06		0.05	0.03	0.08	0.11	0.24	0.42	1.18
10	0.34	0.22	0.19	1.22	0.34	0.22	0.09	0.35	0.44	0.41	1.18	0.32	1.08	0.47	0.52	0.36	0.08	0.1			0.16	0.12	0.02		8.23
11		0.15	0.02																						0.17
15												0.03			0.03	0.02							0.18	0.02	0.28
16	0.31	0.11					0.04							0.09	2.04	0.79									3.38
17												0.02								0.04					0.06
18	0.08	0.03					0.07					0.32													0.5
19												0.32													0.32
20			0.12																						0.12
21	0.03																								0.03
26					0.27																			0.05	0.32
27		0.04	0.17	0.03				0.02	0.02							0.1									0.38
28							0.02																		0.02

Month Total 15.69

Dec-96

Date	12-1 AM	1-2 AM	2-3 AM	3-4 AM	4-5 AM	5-6 AM	6-7 AM	7-8 AM	8-9 AM	9-10 AM	10-11 AM	11-12 AM	12-1 PM	1-2 PM	2-3 PM	3-4 PM	4-5 PM	5-6 PM	6-7 PM	7-8 PM	8-9 PM	9-10 PM	10-11 PM	11-12 PM	Daily Total
1																			0.03		0.02				0.05
4							0.09																		0.09
10																								0.26	0.26
11	0.19		0.02	0.33												0.02									0.56
16					0.02	0.08		0.02																	0.12
20																						0.02			0.02
21									0.06															0.03	0.09
24									0.03								0.04	0.07			0.2			0.03	0.37
25	0.25	0.06	0.1																						0.41
26																	0.02								0.02
27		0.03			0.11																0.03				0.17
28												0.02													0.02
29			0.05	0.06					0.11	0.09		0.17	0.03										0.05		0.56
30							0.08	0.02	0.03															0.02	0.15
31	0.07																								0.07

Month Total 2.96

Month	**Rainfall**
January	5.74
February	2.44
March	2.06
April	5.04
May	0.28
June	0
July	6.74
August	6.07
September	15.69
October	2.36
November	7.54
December	2.96
Total	**56.92**

Appendix K Informational Pamphlet

Green Roofs

- A green roof is a vegetated roof cover which consists of four common layers; a waterproofing layer, a drainage layer, growing media, and plants. Green roofs can either be part of a buildings original design or retrofit on top of an existing roof. Green roofs offer several advantages over traditional roofs which are listed below.

Advantages of Green Roofs

- Lower cooling costs due to reduced roof temperature
- Reduce the ambient air temperature above roof
- Protect the roof from ultraviolet damage
- Reduce storm water runoff
- Add aesthetic appeal
- Replace vegetation lost in original construction

- Many corporations are investing in environmentally friendly building methods to improve their public image and to gain business from environmentally minded consumers. The Ford Motor Company incorporated green roofs in their new Dearborn, Michigan plant shown here.

greenbuildings-d05@wpi.edu