COST-BENEFITS ANALYSIS AND LIFE CYCLE ASSESSMENT OF GREEN ROOFS: A CASE STUDY

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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To all whom enlightened my way by their knowledge, love, patience, and support

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LIST OF ABBREVIATIONS

BEM	Building Energy Modeling
CSO	Combined sewer overflow
CSSs	Combined sewer systems
EPA	Environmental Protection Agency
ERU	Equivalent residential unit
ET	Evapotranspiration
GHG	Greenhouse gas
IE	Impact estimator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LID	Low impact development
MS4s	Municipal separate storm sewer systems
SSSs	Sanitary sewer systems
TRACI	Tool for Reduction and Assessment of Chemical and Other Environmental Impacts
UHIE	Urban Heat Island Effect

Abstract of Thesis Presented to the Graduate School
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Major: Construction Management

Multiple environmental and social benefits can be achieved by using a green roof instead of conventional roofs, especially in the stormwater management aspect and building energy consumption reduction. To better understand the benefits, cost-effectiveness, and environmental impacts of a green roof, a case study is included in this thesis. The objective building is Rinker Hall located on the University of Florida campus, Gainesville, Florida. Previous research shows that the green roof can retain 34% to 94% of rainfall within its growth medium in Gainesville. To compare the influence of green roof on building energy consumption, two energy models are created through eQuest in this study. One is Rinker Hall with a conventional white roof as a benchmark model. Another one is Rinker Hall with an extensive green roof. The simulation results determined that the application of a green roof influences energy consumption due to space heating and space cooling. About 9496 Kwh/year of electricity can be reduced by using a green roof instead of a conventional white roof for Rinker Hall. To find out if the green roof is more cost-effective, a 50-year cost-benefit analysis was conducted in this study. The service life of a green roof is assumed to be 50 years and the service life of a white roof is assumed to be 20 years. Two main benefits are considered in this analysis: avoided stormwater management fees,

and reduced energy consumption. However, the net savings of the green roof is proven to be negative compared to a white roof due to its high maintenance cost. It should be noted that: 1) not all benefits of green roofs are included in this analysis; 2) the type of shrubs planted on a green roof will have a significant influence on runoff reduction and maintenance requirement. The high maintenance cost may be reduced by choosing species that need minimum maintenance. Athena Impact Estimator for Buildings is a powerful software to compare environmental impacts of different assemblies and materials. In this study, one model of Rinker Hall with a white roof is established as reference model, another model is developed with an extensive green roof to compare the life cycle environment impacts. The results show that by using an extensive green roof, the LCA measures at the product stage, the construction process and the end-of-life stage are all increased. However, these impacts are reduced in use stage, and result in decreases of the overall environmental impacts.

CHAPTER 1
INTRODUCTION

Background

As the average global temperatures increase steadily due to climate change, precipitation will be impacted directly by increases in water vapor and evaporation. The US National Oceanic and Atmospheric Administration (NOAA) determined that the average precipitation has increased by about 6% in the lower 48 contiguous states. The appearance of larger precipitation events has also become more frequent since the beginning of the 21^{st} century. Increase in precipitation will increase surface runoff.

Another reason for increases in runoff is urbanization. In nature, most rainwater is soaked into ground and the rest flows along the surface into rivers and streams. About half of the precipitation in forest area will be absorbed into the ground and 40% will evaporate in to the atmosphere, only 10% flows as runoff (Copeland 2014). With growth of urbanization, however, more and more impervious areas appeared on land surface preventing rainwater infiltration into ground and causing more runoffs.

Excessive runoff caused a great pressure on urban stormwater management system. Traditional drainage infrastructure, also called “gray” drainage infrastructure, is considered as a more expensive approach for urban stormwater management. The cost to construct or maintain traditional drainage infrastructure can be as high as billions of dollars or more (Spatari et al 2011). Due to increase in the amount of stormwater runoff in past two decades, Environmental Protection Agency (EPA) estimates that a total of $106 billion is required to reconstruct and maintain drainage systems to meet the stromwater management demand.

Green infrastructure, also called Low Impact Development (LID), is an alternative approach to manage rainwater runoff through mimicking natural ways. For example, green roofs, permeable roadways, bioretention, street trees are all effective ways to reduce runoff volume. Although the performance of these green infrastructure systems has been well measured in previous studies, the cost-effectiveness and environmental benefits of green drainage infrastructure compared to traditional infrastructures need more investigation. Previous studies demonstrated that green drainage infrastructure of equivalent capacity costs 5%-30% less than conventional infrastructure to construct and about 25% less costly over its life cycle (Kloss and Calarusee 2006; Garrison and Hobbs 2011).

Objective

The objective of this study is to measure the cost-effectiveness and cumulative environmental benefits and impacts of green roofs using building energy modeling (BEM) and life cycle analysis (LCA) tools. Special goals are as follows:

- To find out the energy saving by using a green roof instead of a conventional white roof;
- To compare the cost-effectiveness of green roof and conventional roofs;
- To compare environmental impacts of green roof and conventional roof using Life Cycle Analysis.

CHAPTER 2
LITERATURE REVIEW

Green Roof Introduction and Performance

A green roof is a rooftop that is partially or completely covered with a growing medium and vegetation planted over a waterproofing membrane. It may also include additional layers such as a root barrier, drainage and irrigation systems. Green roofs are separated into several categories based on the depth of their growing media. Extensive green roofs have a growing media depth of two to six inches. Intensive green roofs feature growing media depth greater than six inches (CNT 2010).

Green roof systems can provide a wide range of benefits: (1) reduce storm-water runoff. Green roofs can store significant amounts of water in their growing media; (2) reduce energy use; (3) improve air quality; (4) reduce CO2 emissions; (5) reduce urban heat island effect; and (6) improve habitat.

Based on the literature, rainwater runoff reduction and energy consumption reduction are two main environmental benefits of green roofs.

Life cycle for a green roof is 20-40 years, cost would be $10-$25 per square foot and maintenance would be $0.75-$1.50 per square foot annually. A case study in Long Island City, Queens, NY, showed that a 40-year green roof system retains 10.2 gallons per square foot at a cost of $0.15 per gallon annually (Kolb, 2013).

Urban Stormwater Management

Until the early 20th century, combined sewer systems (CSSs) were used for urban stormwater management, where stormwater and wastewater were designed to share the same pipe network. However, combined sewers can introduce microbial pathogens, nutrients and other water pollution problems when combined sewer overflow (CSO) events occur. Since then, the CSS is divided into new sanitary sewer systems (SSSs) and municipal separate storm sewer systems (MS4s) conveying wastewater and stormwater, respectively (EPA 2004). The separation of CSSs to SSS and MS4 would be very costly, thus CSSs are still in use in most states today (Gibler, 2015).

For much of Florida, rainy season starts from April to October, resulting a huge drainage problem. Municipal separate storm sewer systems (MS4) are widely used in Florida to improve runoff and prevent flooding. A MS4 is a publicly-owned conveyance or system of conveyances (i.e., ditches, curbs, catch basins, underground pipes, etc.) that is designed or used for collecting or conveying stormwater and that discharges to surface waters of the State (Florida Department of Environmental Protection, http://www.dep.state.fl.us/water/stormwater/npdes/MS4_1.htm).

In Gainesville, Florida, the Stormwater Management Utility (SMU) program was developed and established in 1989. Gainesville is in a flat area. Because of this, flooding has threatened this area if drainage system is not well maintained or improved. The program is a fee-based program aimed to ensure that the city has sufficient funding source to plan, construct, operate and maintain its stormwater management system. (City of Gainesville, http://www.cityofgainesville.org/PublicWorks/ProgramsandServices/StormwaterManagement.aspx). Table 2-1 on the next page illustrates how SMU fees are assessed in Gainesville.

The ERU rate stayed growing in past decades. ERU stands for Equivalent Residential Unit. This is the basic Unit for the computation of stormwater service charge and is defined as 2,300 square feet of impervious area. The ERU rate now is $8.56/ERU with one ERU equals 2,300 square feet of impervious area. Credit on the stormwater fees can be obtained by maintaining stormwater retention facilities.

Table 2-1. SMU fees in Gainesville

Residential Properties		Non-Residential Properties
Single Family Attached	1 ERU	Non-Residential properties are assessed according to the amount of impervious area on the property. The number of ERU's is determined by dividing the impervious area by 2,300 square unit.
Duplex Units	1 ERU per dwelling unit	
Condominium Units	1 ERU per dwelling unit	
Apartments	0.6 ERU per dwelling unit	
Mobile Homes	0.6 ERU per dwelling unit	

Runoff Reduction

As the percentage of impervious surface areas increases, more and more rainwater flow to urban drainage systems instead of infiltration and evapotranspiration (ET). By absorbing and retaining rainwater in growing media, green roofs can reduce rainwater runoff significantly, which helps alleviate the pressure of urban drainage system. Gibler (2015) determined that during a 24-month experiment, 54% of 139.8 cm total precipitation can be retained by a 10 cm green roof media in Missouri. The experiment conducted by Gibler (2015) shows that green roof can also help peak flow attenuation, which decreases likelihood of flooding downstream.

The capacity of reducing stormwater runoff differs between extensive green roofs and intensive green roof. Typically, the most important factor influencing the runoff reduction performance is the depth of growing media. The intensive green roof, which is more than 6 inches, can retain more water than an extensive green roof which is generally within 2 to 6 inches. Local climate is another important influential factor. For example, the temperature and precipitation would be lower in winter, which will lead to a low rate of ET and less runoff reduction than summer. Other considerations include the angle of green roofs, growing media's antecedent moisture content and size and distribution of storm events (CNT 2010).

Previous experiments showed that 40% to 80% of annual precipitation can be retained anywhere by green roofs. CNT (2010) determined an estimate equation to help calculate the annual amount of runoff reduced.

[annual precipitation (inches) * GI area (SF) * %retained] *144 sq. inches/SF * 0.00433 gal/cubic inch = total runoff reduction (gal)

At the national scale the cost to transport and treat water and wasterwater accounts for nearly 4% of the US electricity demand (Electric Power Research Institute, 2002). Therefore, Green roofs are not only as an approach to reduce stresses on water management system and water pollution control facility infrastructure, but also as a strategy to reduce the demand on energy usage and carbon footprint. Based on 2006 data, the City of New York (2008) estimates that wastewater transport and treatment add up to 17 percent of New York City's aggregate greenhouse gas (GHG) emissions. Spatari et al. (2011) conducted a long-term test for one low impact development (LID), which is a 6.75-acre block in New York City, and determined that the energy savings and avoided greenhouse gas (GHG) from reduced runoff are 7.3 GJ and 0.4 metric tons, respectively. This slight benefits make for a very slow payback time.

However, it is important to be noted that in Florida, CSSs is separated to SSSs and MS4s, which means that transportation and treatment cost for only stormwater would be much lower than that in New York.

Energy Consumption Reduction

Compared with a conventional roof, the growth media of a green roof can perform as additional insulation and reduce heating requirement in winter. By absorbing and reflecting solar radiation, green roof has a significant effect on reducing the temperature of roof surface, which reduces the cooling requirement during warm-weather season. The evaporative cooling from plants and growth media also help reduce the surface temperature. A study of an eight-story residential building in Madrid found that when green roof applied, 1.2% of annual building energy consumption would be reduced. The bulk of the consumption reduction comes from reduced summer cooling costs, which would be 6% less than the conventional roof (Saiz et al. 2006). In Gibler's case study, 16 thermocouples were used to measure the temperature data for each of the green, black roof, and white roofs. Figure 1 illustrates surface temperatures of these three roofs during August 30-31, 2014. The results showed that the green roof always has the lowest surface temperature compared with white roof and black roof. And after precipitation the difference get the peak value due to the evaporative cooling effect.

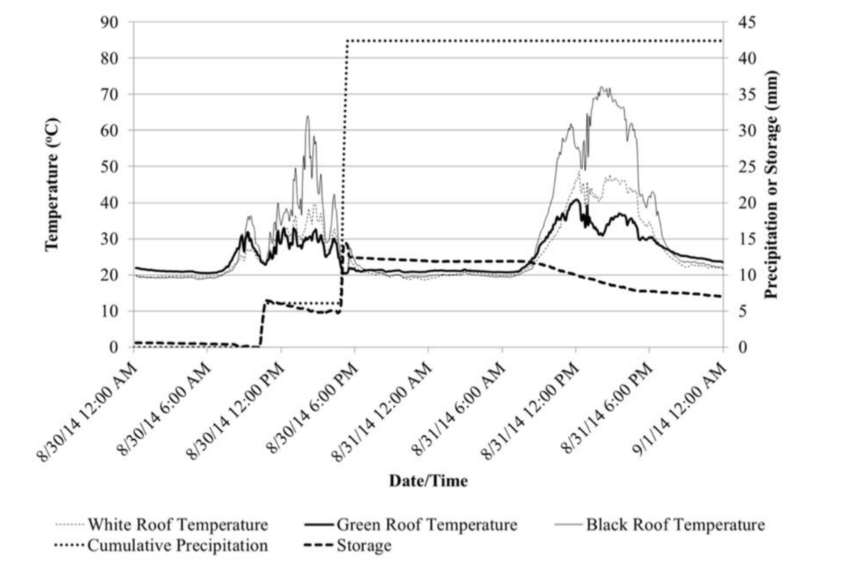

Figure 2-1. Surface temperature of multiple roof types. (Source: Gilbler 2015)

Some previous studies determined that 70%-90% of heat flux can be reduced in summer and approximately 10%-30% reduced in winter by applying green roofs.

CNT (2010) gives an empirical equation to estimate energy saving of green roofs compared to a conventional roof:

annual number of cooling degree days (°F days) * 24 hrs/day * ΔU = annual cooling savings (Btu/SF)

annual number of heating degree days (°F days) *24 hrs/day * ΔU = annual heating savings (Btu/SF)

Where:

For conventional roofs: R = 11.34 SF * °F * hrs/Btu.

For green roofs: R = 23.4 SF * °F * hrs/Btu (Clark et al. 2008).

$$\Delta \mathrm{U} = \left(\frac{1}{\mathrm{R}_{\text{conventional roof}}}\right) - \left(\frac{1}{\mathrm{R}_{\text{green roof}}}\right) \text{ or}$$

$$\Delta \mathrm{U} = \left(\frac{\mathrm{Btu}}{11.34 * \mathrm{SF} * \ {}^{\circ}\mathrm{F} * \mathrm{hrs}}\right) - \left(\frac{\mathrm{Btu}}{23.4 * \mathrm{SF} * \ {}^{\circ}\mathrm{F} * \mathrm{hrs}}\right)$$

The performance on energy saving is significantly influenced by building location and solar radiation. In Gainesville, Florida, the 1981-2010 normal for annual cooling degree days is 2639 °F$days$, normal for annual heating degree days is 1218 °F$days$ (National Climatic Data Center of the National Oceanic and Atmospheric Administration, station CHCND: USW 00012816 http://lwf.ncdc.noaa.gov/oa/documentlibrary/hcs/hcs.html).

Castelton et.al (2010) summarized several key factors for energy saving potential assessment: 1) more heat gain/loss into/out of the building will be achieved when the soil medium is thicker; 2) a less dense soil has more air pockets which makes it a better insulator; 3) the moisture content of the soil will reduce heat loss through evapotranspiration. Teemus and Mander (2008) measured the layer’s temperature of a green roof and a regular roof from June 2004 to April 2005. They found that an extensive green roof can protect the roof membrane from intensive solar radiation and extreme temperatures. During summer the temperature fluctuations of 100-mm-thick substrate layer of a green roof significantly decreased compared with the surface of the bituminous roof. During autumn and spring the soil protect the roof's membrane from rapid cooling and freezing. A case study of a nursery school building equipped with a green roof in Athens, Greece indicated that the installation of a green roof significantly contributes to the building efficiency. The cooling load variation range for non-insulated building is -27% to -87% through May to September. However, the impact of the green roof system on heating load was found insignificant (Santamouris et.al, 2007).

Other Environmental Benefits

Although there are lots of environmental benefits provided by green roofs, only few studies monitored and documented them through experiment. Other environmental benefits include air quality improvement, moderation of Urban Heat Island Effect (UHIE), mitigation of global warming, e.g. For instance, plants on the roof reduce gaseous pollutants and provide air quality benefits. The performance on carbon sequestration reduces the amount of carbon dioxide in atmosphere, preventing global warming and climate deterioration.

Carbon Sequestration

Vegetation of green roofs can sequestrate carbon dioxide directly. Reduced energy consumption is also another main source to reduce carbon footprint. Getter (et.al 2009) monitored four green roofs in Maryland and eight green roofs in Michigan and found that about 375 g C can be sequestrated by per square foot of extensive green roof. Selected species, application of fertilizer, and irrigation, e.g. can slightly influence the sequestration effect. Although it is hard to determine the monetary value of carbon dioxide emissions and there is a wide range of the estimates, which starts from $12/Mg to as high as $95/Mg, the value of

$85/Mg is the most widely used when evaluating the economic impact of climate change and valuing carbon dioxide emissions (Wise et.al 2010).

Air Quality Improvement

Different species planted in green roof have different rates to take up pollutants. Local climate is also another big factor influencing air quality improvement effects. Generally, weather with longer warm seasons will lead to greater air quality improvement. Table 2-2 shows A range of values as an order of magnitude approximation of annual pounds of pollutant removed per square foot of green roof.

Table 2-2. Range of annual pounds of pollutant removed by per square foot of green roof

	Low (lbs/SF)	High (lbs/SF)
NO_2	3.00×10^{-4}	4.77×10^{-4}
O_3	5.88×10^{-4}	9.20×10^{-4}
SO_2	2.29×10^{-4}	4.06×10^{-4}
PM-10	1.14×10^{-4}	1.33×10^{-4}

(Source: CNT, 2011)

Urban Heat Island Mitigation

Evaporative cooling effects from water retained in growth media and plants can help mitigate urban heat island effect.

Building Assessment Methods

To assess the performance of a building during preconstruction phase is critical, especially for sustainable buildings. Srinivasan et al. (2014) provides multiple building assessment methods developed, including Assessment Frameworks, Evaluation Tools and Metrics.

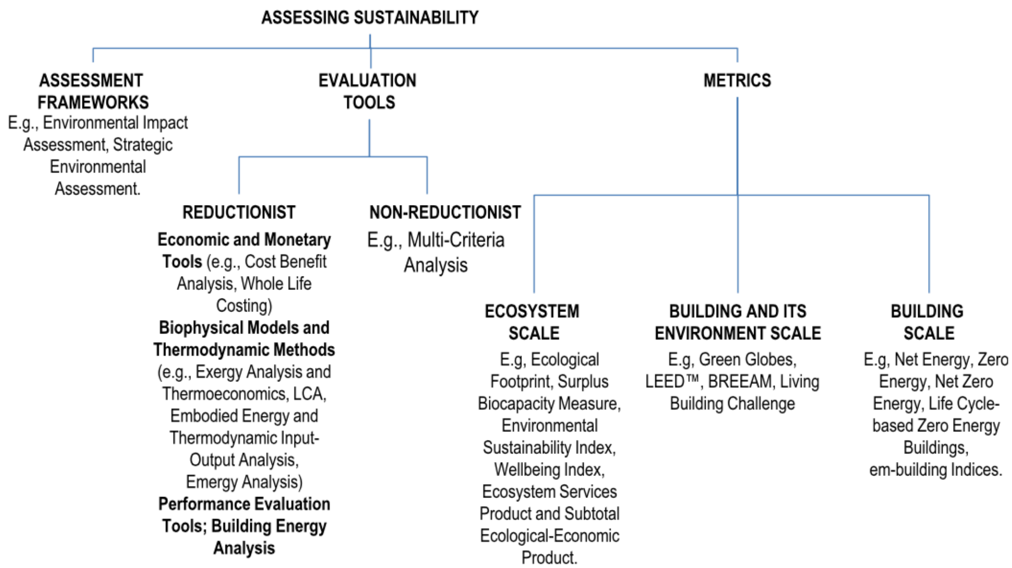

Figure 2-2. Building Assessment Methods (Source: Srinivasan et al. 2014)

The Assessment Frameworks are integrated and structural models which are typically used for comparing various alternatives for projects. Evaluation Tools are divided into two sub-categories-reductionist and non-reductionist. Reductionist tools, which convert a complex system into several smaller set of variables and integrating its measurable characteristics, include economic and monetary tools, biophysical models and thermodynamic methods, performance evaluation tools and building energy analysis. Economic and monetary tools use market currencies as a metric, while biophysical tools are out of eco-centric perspective which use physical units. The last second level sub-categories are metrics at various scales. For example, ecological footprint, environmental sustainability index and Wellbeing index are all measured at ecosystem scale. The two most commonly adopted rating system in the USA, Green Globes and LEED, are measured at building and its environment scale. The last condition is based on building scale including net energy concept, zero energy concept, net zero energy concept, e.g.

Cost-Benefit Analysis

Considering that a lot of characteristics such as green roof types, location, weather conditions, e.g., can affects the performance of green roofs, Bianchini and Hewage (2012) conducted the cost-benefit analysis of green roofs through Monte Carlo simulation. A comprehensive benefit inventory was included in their analysis. All benefits from green roofs are grouped as private benefits and social benefits. Private benefits include tax reduction, storm water retention, avoided storm water in drainage system, energy reduction from cooling and heating, longevity benefit. Social benefits include air pollution, carbon reduction, air quality improvements, reduction of infrastructure improvement costs, reduction of flood risk and habitat creation, provision of recreational space, mitigation of urban heat island effect and aesthetics. In their analysis, each analyzed parameter has a uniform distribution or triangular distribution and then the life cycle analysis was conducted for 10,000 simulations. The most probable payback period for extensive roofs are 4.6 years considering only personal benefits and 4.2 years with both social and personal benefits (Bianchini and Hewage, 2012).

For most previous cost-benefit analysis of green roofs, however, researchers did not include so many benefits due to missing data or their minimum effects.

Only a small amount green roofs are installed in North America because of the high initial cost. Multiple previous research has determined that stormwater runoff reduction is the most significant feature of extensive green roof systems. A cost-benefit analysis of a 10,000-square foot extensive green roof show that total savings using an extensive green roof would be $8.00/sf over 40 years. Three parts are included in this study: the investment costs, the operation benefits and additional savings (avoided wastewater charges, sales tax, reduction in insurance, e.g.) (Breuning, 2013)

Life Cycle Assessment (LCA)

LCA Introduction

LCA, known as life cycle assessment (as well as life cycle analysis) is a quantitative analysis of environmental impacts from all stages of raw material. As part of the ISO 14000 environmental management standards, LCA is an important support tools in international environmental management and product design.

Object of assessment, method of assessment, applied purpose and characteristics are four principles of LCA. Object of LCA refers to the environmental impacts of products or services instead of the environmental quality and this is the most difference compared with the environmental quality in environmental science. Additionally, the assessment scope of LCA is required to cover the whole life cycle of product instead of one of several special phases. The main mind of LCA method is that by collecting environmental inventory data related product and considering the resources consumption, human healthcare and ecological impacts, the assessment can be determined and quantitative. Furthermore, the appropriate time and way to improve products' environmental performance need be found and analyzed. The LCA is based on detailed environmental inventory database, which is the most fundamental characteristic of LCA method and the guarantee to make LCA more subjective and scientific. Generally, all different subjects can operate the assessment work or quote the LCA assessment conclusion out of their different goals.

There are some utilities of LCA in SETA and ISO. For example, (1) help provide the general condition of the interaction between product system and environment; (2) enhance the understanding of environmental impact from product system; (3) provide a foundation for stakeholders to communicate with each other; (4) supply determination information about friendly environment for decision maker, including the potential environmental impacts, the time and way to improve environmental performance and basis for selection of products and techniques.

Compared with other administrative methods and management tools, LCA has its own trait as a tool of environment management. First, LCA requires no passive inspection or supervision of any companies. It prefers to encourage them to be more active and combine the environmental factors to their determination process. Under this condition, although LCA is not an administrative or legally coercion, it works well in both research and utility fields. On the one hand, LCA plays a crucial role in the product environmental assessment and on the other hand, it is a result of a deep development of environment protection concept.

There are four phases of a life cycle assessment and each one relates to the others. The first phase is goal and scope definition, which is the first and the most crucial part for a LCA study. Goal definition illustrate the reason and applied intention of LCA, scope definition describe functional units, system boundaries, contribution of database, data requirement e.g. This phase is key to the whole assessment because it directly decides the width and scope of a LCA study and considering the repeat characteristic of LCA, some remedy and adjustment are also needed to make it more accurate. The second phase is inventory analysis, which is a process of building inventory of input and output data. Impact assessment is to evaluate the environmental impacts of product life cycle based on the subsequences of inventory analysis. The last phase is interpretation which identifies significant issues based on the inventory analysis and impact assessment, evaluates the study considering completeness and sensitivity checks as well as achieves conclusions, limitations and recommendations.

For construction material, the goal and scope concentrate on resources and energy consumption of the related materials as well as pollution problems. Inventory analysis refers to the collection of products' input and output during the whole life cycle including resources and energy consumption, exhaust of waste gas and waste water, solid waste and other environmental emissions. Some assessment items like GER, GWP and SWB are usually involved in impact assessment phase and regarding to the result, improvement suggestions on raw materials, manufacturing design and construction management are put forward to complete the whole assessment.

By identifying and quantifying the consumption and emission of energy and product during the whole process of life cycle, evaluating the impacts resulted from consumption and emission to environment and discussing the possibility to reduce these impacts, LCA mainly concentrates on the environmental impacts on economic system health, human health and resources consumption field.

The functional unit is the most important concept for comparative studies because it is the basis for comparison. Flynn and Traver (2011) used Drainage Area as the functional unit in their study when comparing different Best Management Practices (BMPs).

Although LCA is a powerful tool to analyze the environmental impacts on quantitative aspect, it has some limitations on applied range, assessment range, assessment method as well as time and site aspect. As a tool of environment management, LCA is not applicate for all circumstances. In other words, LCA will not solve all problems occurred during the decision-making process. It only considers some ecological and resources consumption problems and does not include technical, economic or social impacts. For example, quality, function, cost, and benefit are all not included in LCA assessment.

To better figure out both economic and environmental advantages of green roofs, Cost-Benefits Analysis will be used as an auxiliary tool in this thesis.

LCA of Green Roofs

Saiz et.al (2006) conducted LCA of common flat roof (BFR), white roof (BWR) and green roof (BFR) located in downtown Madrid, Spain. The construction phase and decommissioning phase are not included in their analysis due to the lack of data. In other comparable studies, however, it is determined that the impacts from these two phases only make a small contribution over the whole life. Saiz et.al (2006) compared the three roof types by conductance, thermal capacity and solar absorptance and found that the key factor of a green roof is its low solar absorptance. Only 1% reduction of annual energy consumption was achieved by using green roof instead of common flat roof. However, the author noted that the green roof area was only 16% of the building's exposed surface area. A low-rise building with a lager roof-to-envelope ratio should have greater energy reductions. The LCA shows that the use phase leads more than 50% of the total environmental impacts over the whole life. For abiotic depletion, acidification, terrestrial ecotoxicity, and eutrophication categories, the use phase accounts for 71-83% of the total impacts.

A study conducted in Pittsburgh, PA climate shows that the energy use reduction is achieved mainly due to the lower thermal conductivity of green roofs. The extensive and intensive roofs have only one-half of the environmental impacts of conventional roof. Impact 2002+ results indicate that human health represents 70-90% of the total score among all impact categories. Although it is not determined that if life cycle cost (LCC) of a green roof is lower than a conventional roof, green roofs are the environmentally preferable choice when constructing a building for the longer life span and small reduction in energy demand (Kosareo and Ries, 2006).

CHAPTER 3
METHODOLOGY

eQUEST Energy Analysis Software

To simulate the energy consumption of Rinker Hall with both conventional roof and green roof, eQUEST 3.65 as an energy analysis software is used in this study.

eQuest Introduction

eQuest is a powerful software to simulate energy consumption of buildings. The software includes a building creation wizard, an energy efficiency measure (EEM) wizard, and graphical reporting with a simulation “engine” derived from the latest version of DOE-2.

Modeling

First, 2D drawings are used to create the 3D building envelope. Then, the envelope parameters, such as exterior wall layer, roof layers, glazing, were specified. Occupancy, equipment density, lighting density and others were also assumed and entered to the software. The California ACM Manual was used to create annual schedule of heating, cooling lights, equipment, fans, occupancy and hot water. Finally, the energy consumption of the building model with different roof systems were measured and compared. More details can be found in Zeng et.al (2016).

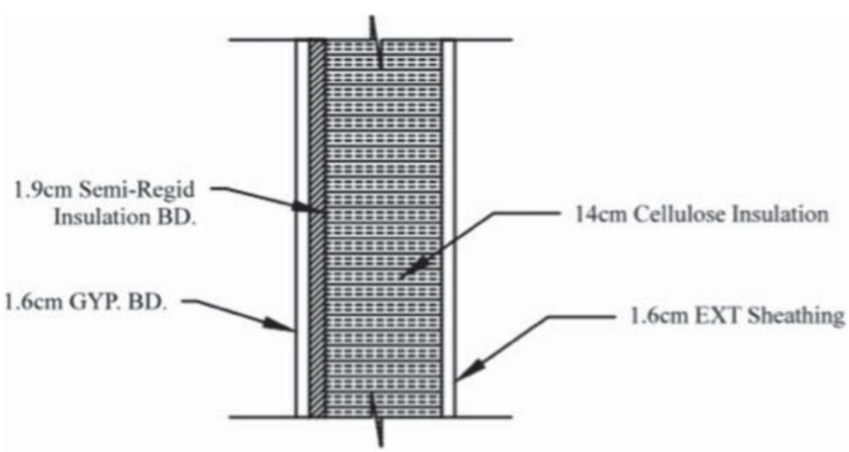

Figure 3-1. Exterior wall components of Rinker Hall

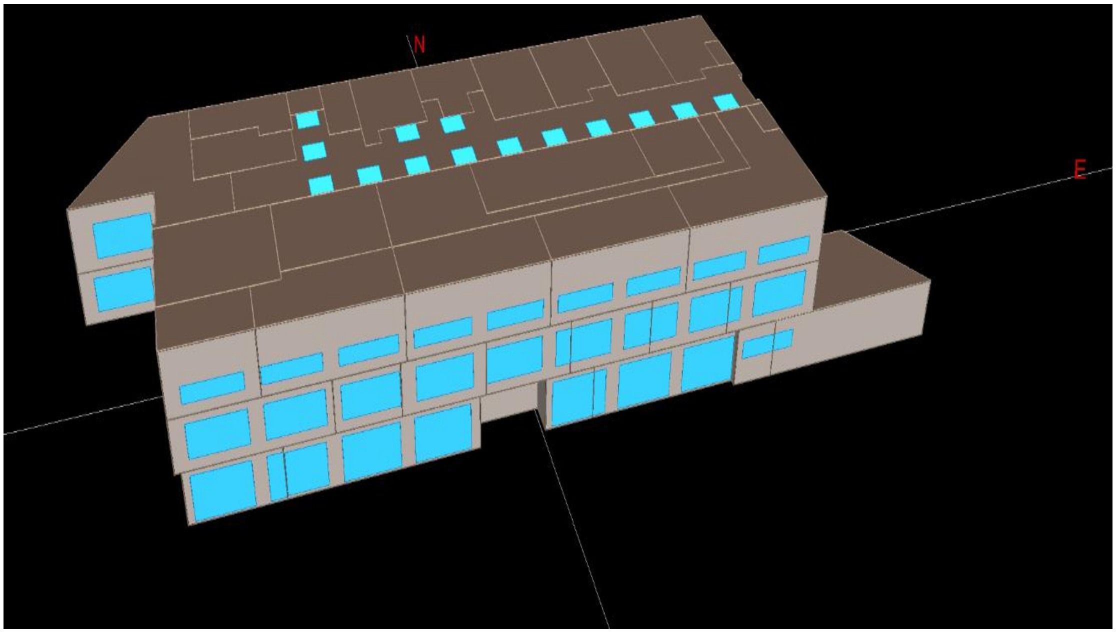

Figure 3-2. 3D model of Rinker Hall

Saiz et.al (2006) compared common flat roof, white roof and green roof by three characters: conductance (W/m^2 ℃), thermal capacity (KJ/ ℃), and solar absorptance. The results show that white roof and green roof have a much lower solar absorptance than grey common roof. All these three characters of green roof are slightly lower than those of white roofs. (Table 3-1)

Table 3-1. U-value and solar absorptance of three roof types

	U Value	Solar Absorptance
Flat Common Roof (Grey)	0.088	0.8
White Roof	0.088	0.4
Extensive Green Roof	0.043	0.37

(Source: Saiz et.al, 2006)

In this study, the independent parameters entered are U- value and solar absorptance of white roof and extensive green roof. (Figure 3-3 and Figure 3-4)

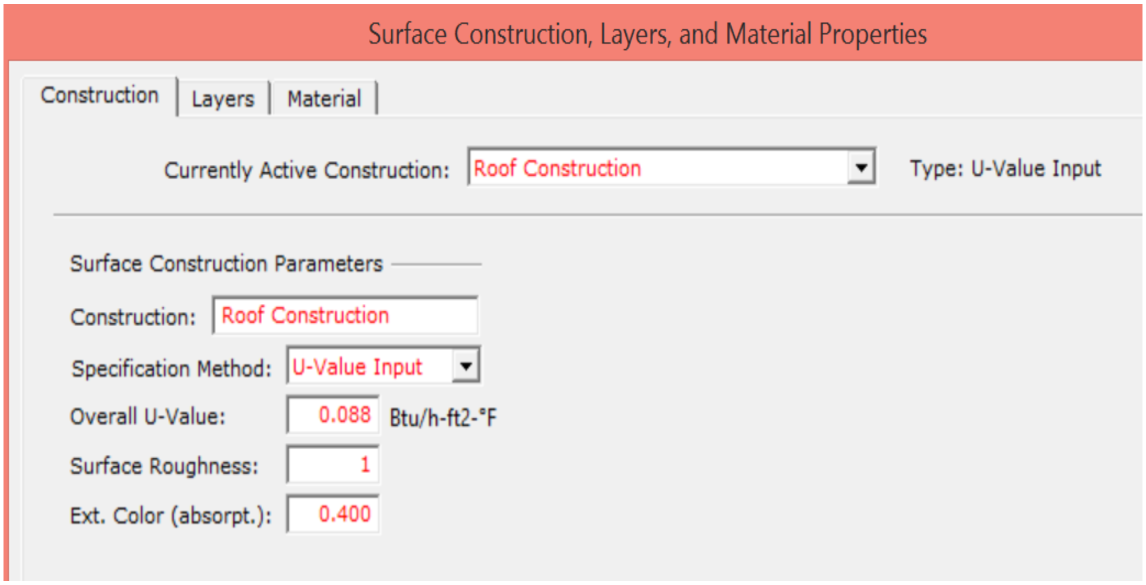

Figure 3-3. Data input for white roof

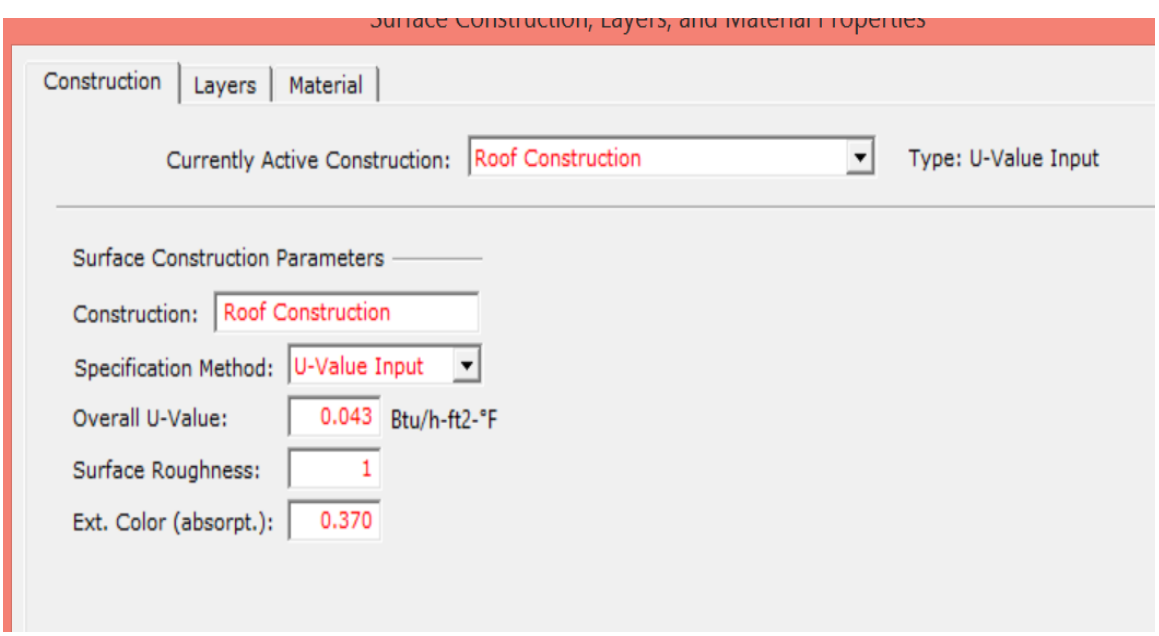

Figure 3-4. Data input for green roof

Results: Part One

Hourly reports of quick roof conduction gain are created for both models. The results showed that green roofs reduce heat loss into outside environment in winter and prevent heat gain in summer (Figure 3-5, Figure 3-6)

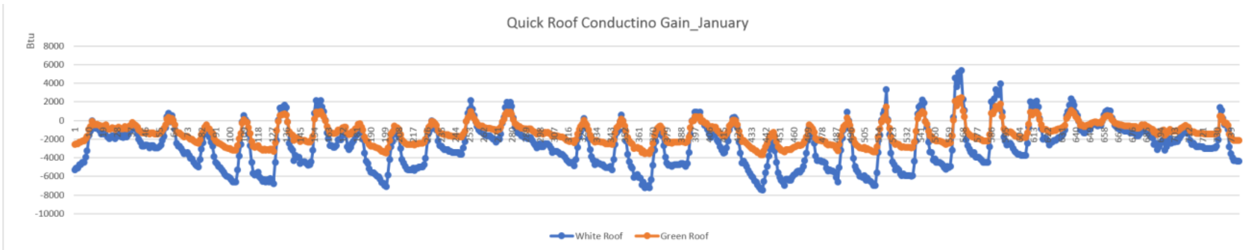

Figure 3-5. Quick roof conduction gain of white roof and green roof in January

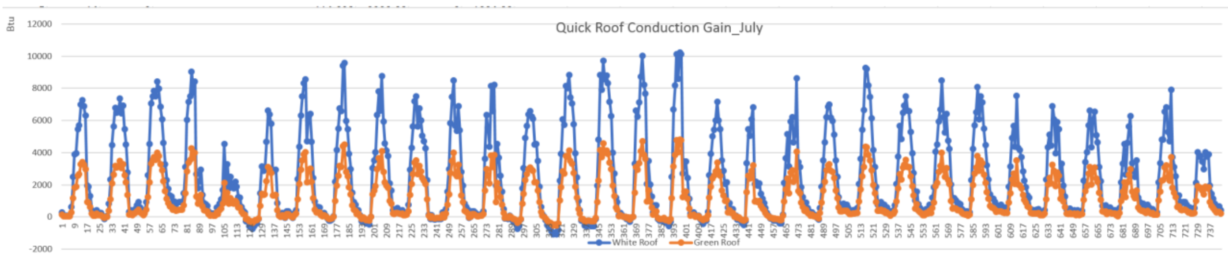

Figure 3-6. Quick roof conduction gain of white roof and green roof in July

Two typical days are analyzed: January 15th, and July 15th (Figure 3-7, Figure 3-8).

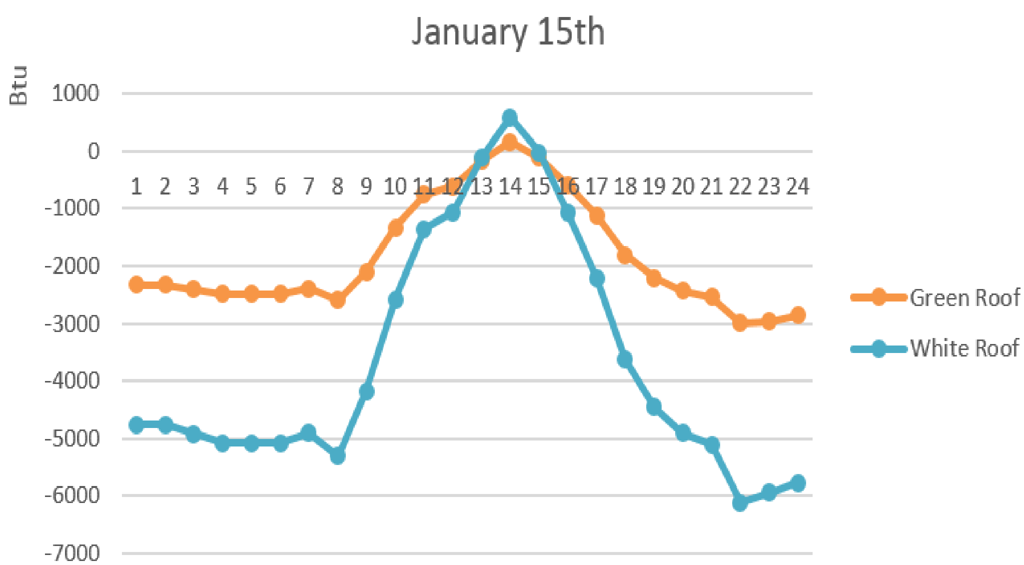

Figure 3-7. Quick roof conduction gain of white roof and green roof on January 15th

From 1:00 am to 8:00 am, there is a heat loss through roof conductions. The heat loss of a white roof is about twice than that of a green roof. After 8:00 am the heat loss starts to decrease. At around 2:00 pm the quick roof conduction gain has a peak value. After 2:00 pm the quick roof conduction gain starts to decrease and starts to lose heat into outside. As can be seen from the figure, when the temperature inside is higher than that of outside, more heat is lost through a white roof than a green roof. When the temperature inside is lower than that of outside, a green roof reduces more solar heat gain than a white roof. During winter period the significant benefit of a green roof is to prevent more heat loss through its layers.

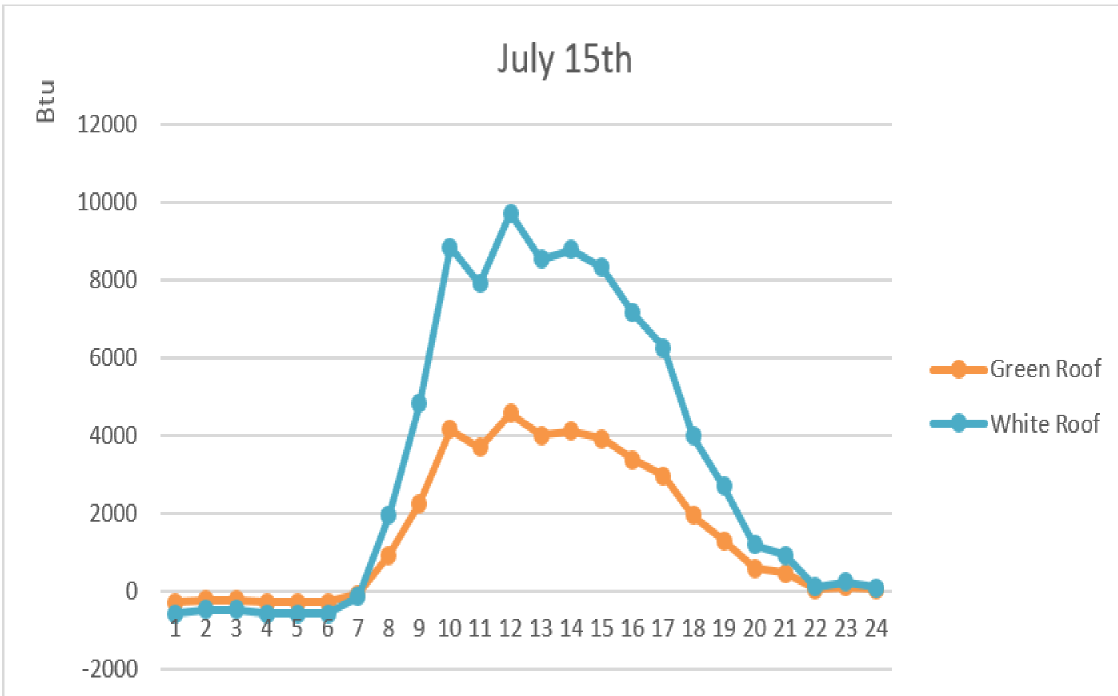

Figure 3-8. Quick roof conduction gain of white roof and green roof on July 15th

The significant benefit of a green roof during summer seasons is the reduction of solar heat gain. From 10:00 am to 3:00 pm the solar heat gain is around 4,000 Btu for the green roof and around 9,000 Btu for the white roof.

Results: Part Two

Energy consumption is simulated for Rinker Hall with a white roof and a green roof. Energy consumption of Space Heating, and Space Cooling of the model with green roof have a slight reduction compared with that of white roof (Table 3-2).

Table 3-2. Differences of energy consumption using conventional white roof and green roof (MMBtu)

	White	Green	Change	Percentage
Lights	392	392	0	0.00%
Misc. Equipment	95.1	95.1	0	0.00%
Heating	42.4	31.2	-11.2	-26.423%
Cooling	2950	2932	-18	-0.61%
Pumps &Aux	463	463	0	0.00%
Vent Fans	529.5	526.7	-2.8	-0.53%
DHW	30.4	30.4	0	0.00%
Total	4502.5	4470.1	-32.4	-0.72%

The application of a green roof reduces energy consumption for heating, cooling and vent fans. The total energy saving is 32.4 MMBtu, which is 9495.5 KWh.

Cost-Benefits Analysis

Initial Cost of Green Roof & White Roof

The cost of green roofs varies significantly. In British Columbia, Canada, the costs for a standard extensive green roof varies from $130/$m^2$ to $165/$m^2$ (Bianchini and Hewage, 2012). Carter and Keeler (2008) conducted a life cycle cost-benefit analysis of extensive green roofs in Athens, GA and they used $158.82/$m^2$ for green roofs. In this study, $130/$m^2$, which is equivalent to $12/$ft^2$, is used regarding to the roof area and local labor rate. The 2017 TPO roof price in Gainesville varies from $4.00/$ft^2$ to $5.55/$ft^2$ for various levels – the basic, better and the best (http://www.remodelingexpense.com/costs/cost-of-tpo-roof/). In this study, $\$5/ft^2$ is used for TPO roofs.

The roof area of Rinker Hall is 14,760 square feet. The cost of a green roof is then estimated to be $177,120 and the cost of a TPO as $73,800.

Maintenance Requirement

Although the planted species are all resistance to Gainesville environment and have low maintenance requirements, special maintenance and normal visits are necessary to keep the green roof's regular operation. Special maintenance includes the cost for weed control and incidental materials which could be estimated as $400 per year. The normal visit schedule is divided into two time periods due to the plant growth. The first period is from October to March which needs 1 labor hour biweekly, the second period is from April to September which needs 1 labor hour weekly. The total labor hour is calculated as 6 months x 2 LH/month + 6 months x 4 LH/month = 36 labor hour. The labor rate is estimated as $26/hour (including 30% fringe benefits). Thereby the annual maintenance cost would be 36 labor hours x $26/hour = $1,336.

White roof has a minimum maintenance requirement. However, the service life of a conventional White roof is assumed to be only a half of a green roof. In this study, the service life of a green roof is 50 years, and the service life of a conventional white roof is assumed to be 20 years, which means that in year 20 and year 40, there is a replacement requirement of white roofs.

Benefits of Green Roofs

Among a several number of benefits provided by green roofs, stormwater management benefits and energy saving are the two main aspects monitored and measured in recent literature. In this study, three benefits of green roof are considered: stormwater management benefit, energy saving benefit, and carbon sequestration.

Stormwater Management

Green roof can significantly reduce rainwater runoff by absorbing and retaining water in its soil as well as evapotranspiration. Most research shows that the 10% to 90% of runoff can be reduced by green roofs. In Gainesville, the average annual precipitation is 47.37 inches (U.S. climate data). Assume that 60% of the rainfall does not flow into sewer system, then the quantity of retained water is 47.37 inches x 14,760 SF x 60% x 144 sq. inches/SF x 0.0043 gal/cubic inch = 433 Kilo gallons per year.

In Gainesville, FL, stormwater management utility program is established in 1989. Credit on the stormwater fees can be obtained by maintaining stormwater retention facilities. Long (2011) determined that at most time, the retention rainfall in growth media and retained water in the cisterns can avoid overflow. So, if this stormwater retention facility is approved, the stormwater management fee can be avoided as a benefit. Non-Residential properties are assessed regarding the amount of impervious area on the property. The number of ERU's is determined by dividing the impervious area by 2,300 square unit. In this study, the area of green roof on top of Rinker Hall is 14,760 square foot, 6.42 ERU. The avoided stormwater management fee due to Rinker Hall green roof based on ERU rate of $8.56 per month is $55 per month or $660 per year.

Energy Saving

The energy modeling of Rinker Hall was created and used to determine the energy saving from heating and cooling using a green roof. The results show that compared with conventional white roof, green roof can reduce energy used for heating and cooling up to 32.4 MMBtu/year, which is equivalent to 9496 KWh.

The average commercial electricity rate in Gainesville is 14.07¢/kWh, so the monetary value of energy saving is $1336/year.

Carbon Sequestration

Based on previous literature, a range of 0.0332 lbs C per square foot to 0.0344 lbs C per square foot is assumed to be sequestrated by green roof annually (CNT,2011). It is proved that carbon sequestration effect can be influenced by climate and longer growing season will see a greater effect. Considering the weather of Gainesville, FL, the upper range is used in this study.

The interagency group estimates the social cost of carbon based on three integrated assessment models: the FUND, DICE, and PAGE. Climate processes, economic growth, and feedbacks between the climate and the global economy are all included in their considerations. The estimates are $5, $21, $35, and $65 (in 2007 dollars) for 2010 (Table 3-3). "The first three estimates are based on the average SCC across models and socio-economic and emissions scenarios at the 5, 3, and 2.5 percent discount rates, respectively. The fourth value, which represents the 95th percentile SCC estimate across all three models at a 3 percent discount rate, is included to represent higher-than-expected impacts from temperature change further out in the tails of the SCC distribution." (Appendx 16-A. Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866).

Table 3-3. Social Cost of CO_2, 2010 – 2050 (in 2007 dollars)

	Discount Rate			
	5%	3%	2.50%	3%
Year	Avg	Avg	Avg	95th
2010	5	21	35	65
2015	6	24	38	73
2020	7	26	42	81
2025	8	30	46	90
2030	10	33	50	100
2035	11	36	54	110
2040	13	39	58	119
2045	14	42	62	128
2050	16	45	65	136

The choice of a discount rate is an exceedingly difficult question of science, economics, philosophy, and law. Although the discount rate will influence the current value of future damages significantly, what rates to use in this context is still debatable.

The social cost of carbon increases over time because that future emissions will produce more incremental damages at physical and economic systems. For example, the carbon value was $21 per ton in 2010 and increased to $24 per ton in 2015.

Other Benefits

There are many other benefits provided by green roofs like sequestration of carbon dioxide, improvement of real estate value, multiple community benefits, etc. However, it is usually hard to convert these benefits into monetary value, and based on previous literature, the contribution of these benefits is usually less realizable. In this study, other benefits are not considered.

Cost-Benefits Analysis

2.5% is used for inflation rate. 4% is used for discount rate and 3% is used for energy inflation rate.

Table 3-4. Cost-Benefit analysis result

Year	Initial Cost	Maintenance	Stormwater Management	Energy Saving	Net Saving	NPV of Net Saving
0	($103,320.00)				($103,320.00)	($103,320.00)
1		($1,336.00)	$660.00	$1,336.00	$660.00	$660.00
2		($1,369.40)	$676.50	$1,376.08	$683.18	$656.90
3		($1,403.64)	$693.41	$1,417.36	$707.14	$653.79
4		($1,438.73)	$710.75	$1,459.88	$731.91	$650.66
5		($1,474.69)	$728.52	$1,503.68	$757.50	$647.52
6		($1,511.56)	$746.73	$1,548.79	$783.96	$644.36
7		($1,549.35)	$765.40	$1,595.25	$811.30	$641.18
8		($1,588.08)	$784.53	$1,643.11	$839.56	$638.00
9		($1,627.79)	$804.15	$1,692.40	$868.76	$634.80
10		($1,668.48)	$824.25	$1,743.18	$898.95	$631.59
11		($1,710.19)	$844.86	$1,795.47	$930.14	$628.37
12		($1,752.95)	$865.98	$1,849.34	$962.37	$625.13

Table 3-4. Continued.

Year	Initial Cost	Maintenance	Stormwater Management	Energy Saving	Net Saving	NPV of Net Saving
13		($1,796.77)	$887.63	$1,904.82	$995.67	$621.89
14		($1,841.69)	$909.82	$1,961.96	$1,030.09	$618.64
15		($1,887.73)	$932.56	$2,020.82	$1,065.65	$615.39
16		($1,934.93)	$955.88	$2,081.44	$1,102.39	$612.12
17		($1,983.30)	$979.77	$2,143.89	$1,140.36	$608.85
18		($2,032.88)	$1,004.27	$2,208.20	$1,179.59	$605.57
19		($2,083.70)	$1,029.37	$2,274.45	$1,220.12	$602.29
20	$73,800.00	($2,135.80)	$1,055.11	$2,342.68	$75,062.00	$35,627.61
21		($2,189.19)	$1,081.49	$2,412.96	$1,305.26	$595.70
22		($2,243.92)	$1,108.52	$2,485.35	$1,349.96	$592.41
23		($2,300.02)	$1,136.24	$2,559.91	$1,396.13	$589.11
24		($2,357.52)	$1,164.64	$2,636.71	$1,443.83	$585.80
25		($2,416.46)	$1,193.76	$2,715.81	$1,493.11	$582.50
26		($2,476.87)	$1,223.60	$2,797.29	$1,544.02	$579.19
27		($2,538.79)	$1,254.19	$2,881.21	$1,596.61	$575.88
28		($2,602.26)	$1,285.55	$2,967.64	$1,650.93	$572.57
29		($2,667.32)	$1,317.69	$3,056.67	$1,707.04	$569.26
30		($2,734.00)	$1,350.63	$3,148.37	$1,765.00	$565.95
31		($2,802.35)	$1,384.39	$3,242.82	$1,824.87	$562.64
32		($2,872.41)	$1,419.00	$3,340.11	$1,886.70	$559.33
33		($2,944.22)	$1,454.48	$3,440.31	$1,950.57	$556.03
34		($3,017.82)	$1,490.84	$3,543.52	$2,016.54	$552.72
35		($3,093.27)	$1,528.11	$3,649.83	$2,084.67	$549.42
36		($3,170.60)	$1,566.32	$3,759.32	$2,155.03	$546.12
37		($3,249.87)	$1,605.47	$3,872.10	$2,227.71	$542.82
38		($3,331.11)	$1,645.61	$3,988.26	$2,302.76	$539.53
39		($3,414.39)	$1,686.75	$4,107.91	$2,380.27	$536.24
40	$73,800.00	($3,499.75)	$1,728.92	$4,231.15	$76,260.32	$16,519.56
41		($3,587.25)	$1,772.14	$4,358.08	$2,542.98	$529.67
42		($3,676.93)	$1,816.45	$4,488.82	$2,628.34	$526.40
43		($3,768.85)	$1,861.86	$4,623.49	$2,716.50	$523.13
44		($3,863.07)	$1,908.40	$4,762.19	$2,807.53	$519.86
45		($3,959.65)	$1,956.11	$4,905.06	$2,901.53	$516.61
46		($4,058.64)	$2,005.02	$5,052.21	$2,998.59	$513.35
47		($4,160.10)	$2,055.14	$5,203.78	$3,098.82	$510.11
48		($4,264.11)	$2,106.52	$5,359.89	$3,202.30	$506.87
49		($4,370.71)	$2,159.18	$5,520.69	$3,309.16	$503.64
50		($4,479.98)	$2,213.16	$5,686.31	$3,419.49	$500.41
					Total	($23,272.53)

The result shows that considering stormwater benefits and energy saving benefits, the green roof is still not cost-effective compared to the conventional roof due to the high initial cost and maintenance cost.

Life Cycle Assessment

LCA Tools Used in this Study: Athena Impact Estimator for Buildings

LCA is a complicated science typically practiced by experts. To make it more accessible for building designers, Athena Impact Estimator for Buildings is released as a simplified tool to conduct LCA. The software applies LCI databases for whole life of buildings including product extraction and manufacturing, transportation, on-site construction and ongoing maintenance and replacement. Building system demolition and end-of-life disposition of materials are also involved in the consideration. Based on the US EPA Tool for Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI v2.1 (2012)) Athena Impact Estimator for Buildings supports the following life cycle impact assessment measures:

- Global Warming Potential -CO2 equivalent mass
- Acidification (Air) Potential - SO2 equivalent mass
- Human Health Criteria –PM 2.5 equivalent mass
- Eutrophication (air & water) Potential - N equivalent mass
- Smog (air) Potential – O3 equivalent mass
- Ozone Depletion (air) Potential – CFC 11 equivalent
- Fossil Fuel Consumption GJ – Total fossil fuel energy

By allowing users to select the project's location from a list of 16 supported locations/regions, appropriate electricity grids, transportation and distances are applied by the software automatically. Expected service life, type of building and whether the building is rental or owner occupied have effects on maintenance and replacement requirement of materials such as window systems, roofing membranes, e.g., so they are all need to be specified at the first step of modelling. The building's annual energy consumption by fuel type can be defined by users in Athena Impact Estimator for Buildings.

The software allows users to create a building by assemblies and envelope perspective. Basic structural assemblies supported by the software include: Foundations, Walls (Exterior infill, load bearing and interior non-load bearing), Beams and Columns, Floors, and Roofs. Envelope material layers such as insulation, vapor barrier, gypsum board, e.g. then can be added to the basic assembly to complete the model.

Modelling: Part One

Gainesville is not available in the IE. Orlando, which is the closest location, is selected in this model. The building type is defined as institutional and the life span is assumed to be 50 years (Figure3-9).

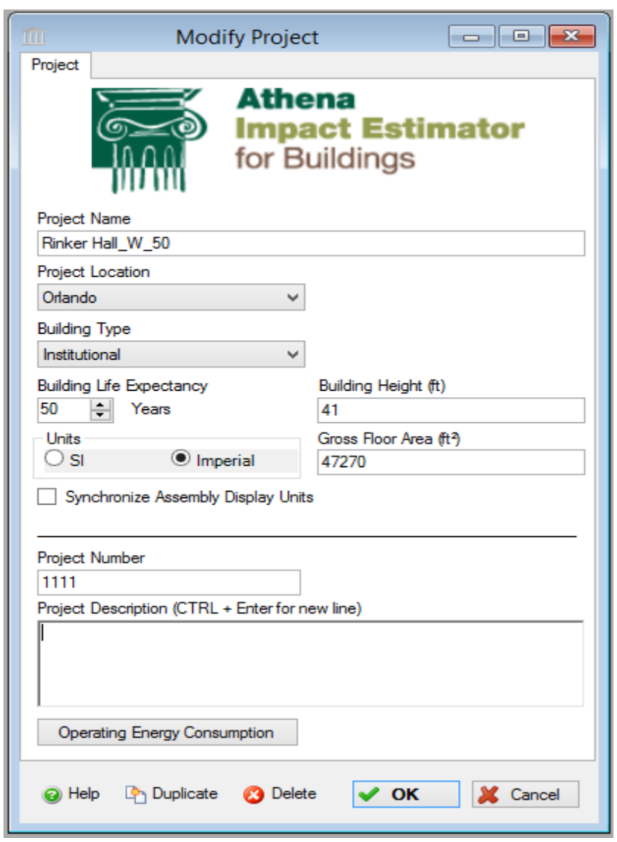

Figure 3-9. Project data input

The 2D drawing of Rinker Hall is used to determine the building assemblies and envelope materials. The building assemblies include: Foundations, Columns and Beams, Roofs and Walls.

After building assemblies and envelope materials are completed, a green roof and a white roof are added, respectively. Typically, a green roof consists of waterproofing membrane, root barrier, drainage mat, and growth media (Figure 3-10).

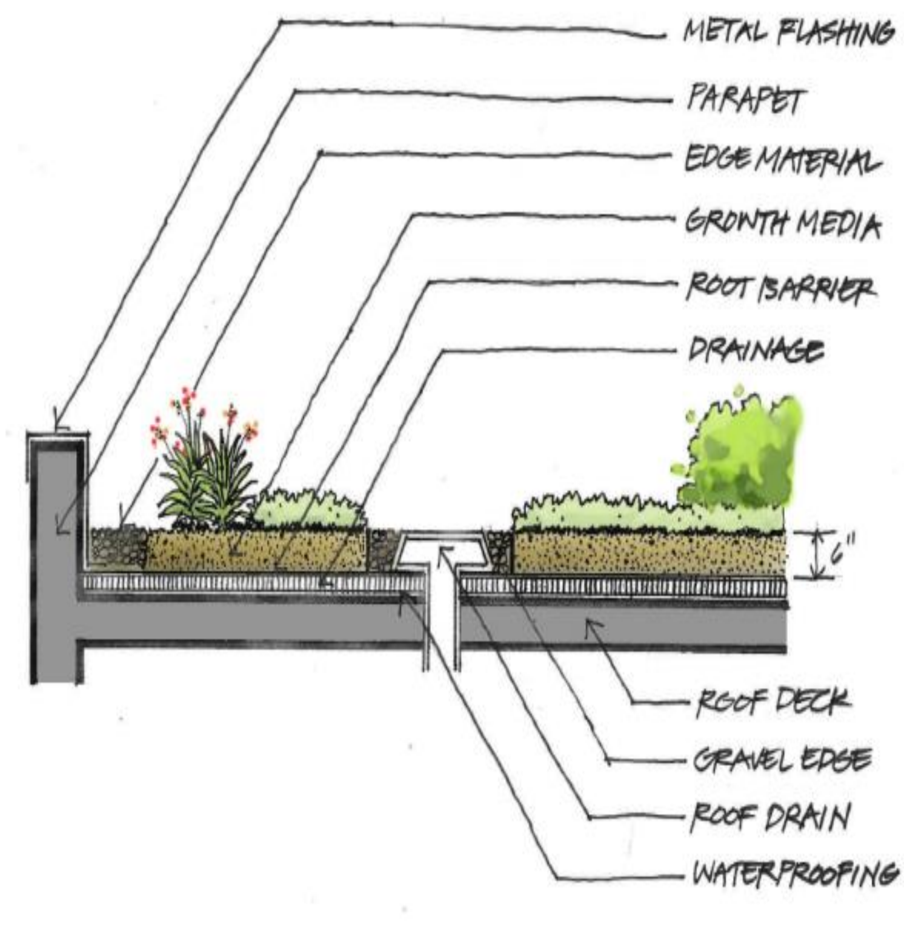

Figure 3-10. Typical Components of Green Roofs

An American Hydrotech Extensive Green Roof System was installed on top of Perry Yard. And the materials on Perry Yard are referred in this study. The material inventory is showed on next page (Table 3-5)

Table 3-5. Material inventory of American Hydrotech Extensive Green Roof System on top of Perry Yard

Materials	Type	Quantity
MM 6125 (lbs)	Waterproofing membrane	4,000
FlexFlash F (sf)	Membrane reinforcement	3,900
Hydroflex RB (sf)	Protection/root barrier	2,910
Floradrain FD25 (sf)	Drainage/H2O retention	2,690
LiteTop Intensive (cy)	6’’ LiteTop intensive soil	55

Hydroflex RB is a rubberized asphalt which is used to protect the membrane from mechanical damage or penetration damage by roots. Generally, it is designed to be embedded into waterproofing membrane - Hydrotech’s MM6125. Over 2,910 sf of Hydroflex RB is needed which is about 2900 lbs. Monolithic Membrane 6215 (MM 6125) is a waterproofing membrane which is a special formulation of asphalts and synthetic rubbers. Flex-Flash F is glass fiber fabric with an asphalt coating which is designed to be used as reinforcement material for MM6125. Its unit weight is 2.4 oz./square yard. The total weight for FlexFlash F needed for Perry Yard would be 65 lbs. Floradrain FD25 is drainage and water storage element made of recycled polyethylene. The weight of this material needed is estimated as 937 lbs.

In Athena’s database, users can select vegetative roof system to modify their green roof model. Although the same layer materials are not available in Athena’s LCI database, the most similar materials are used to establish the green roof model. Table 3-6 shows the green roof layers modified in the model of Athena.

Table 3-6. Envelope of Green Roof

Envelope	Type
Polystyrene Extruded	Insulation
EPDM membrane (60 mil)	Waterproofing
VR 1" Drainage Mat	Water retention
VR 40 mil Root Barrier	Root Barrier
VR Extensive Growing Medium	Growth media

Extruded Polystyrene and EPDM membrane (white, 60mil) are used for the TPO roof of the benchmark model (Table 3-7).

Table 3-7. Envelope of Conventional White Roof

Envelope	Type
Polystyrene Extruded	Insulation
EPDM membrane (white, 60mil)	Membrane

Athena Impact Estimator for Buildings is used to analysis life cycle environmental impacts of Perry yard with a green roof and a conventional white roof. A whole life cycle process was considered including product stage, construction process, use stage and end of life. The LCA measures consists of global warming potential, acidification potential, HH particulate, eutrophication potential, ozone depletion potential, smog potential, and total primary energy. The results for Rinker Hall with a green roof and a conventional white roof are summarized in Table 3-8 and Table 3-9.

Table 3-8. LCA measures of Rinker Hall with a conventional white roof

		PRODUCT (A1 to A3)	CONSTRUC TION PROCESS (A4 & A5)	USE (B2, B4 & B6)	END OF LIFE (C1 to C4)	TOTAL EFFECTS
LCA Measures	Unit	Total	Total	Total	Total	A to C
Global Warming Potential	kg CO2 eq	9.58E+05	1.38E+05	4.72E+07	5.00E+04	4.83E+07
Acidification Potential	kg SO2 eq	4.49E+03	1.36E+03	3.93E+05	5.14E+02	3.99E+05
HH Particulate	kg PM2.5 eq	2.10E+03	8.75E+01	3.38E+04	4.57E+01	3.60E+04
Eutrophication Potential	kg N eq	5.14E+02	9.53E+01	4.26E+03	2.74E+01	4.90E+03
Ozone Depletion Potential	kg CFC-11 eq	9.82E-03	4.76E-04	2.75E-04	2.21E-06	1.06E-02
Smog Potential	kg O3 eq	5.85E+04	3.93E+04	1.59E+06	1.42E+04	1.70E+06
Total Primary Energy	MJ	1.18E+07	1.89E+06	7.85E+08	7.36E+05	7.99E+08
Non-Renewable Energy	MJ	1.16E+07	1.88E+06	7.77E+08	7.33E+05	7.91E+08
Fossil Fuel Consumption	MJ	9.55E+06	1.84E+06	7.32E+08	7.21E+05	7.44E+08

Table 3-9. LCA measures of Rinker Hall with a green roof

		PRODUCT (A1 to A3)	CONSTRUC TION PROCESS (A4 & A5)	USE (B2, B4 & B6)	END OF LIFE (C1 to C4)	TOTAL EFFECTS
LCA Measures	Unit	Total	Total	Total	Total	A to C
Global Warming Potential	kg CO2 eq	1.05E+06	1.43E+05	4.69E+07	5.13E+04	4.81E+07
Acidification Potential	kg SO2 eq	5.05E+03	1.41E+03	3.90E+05	5.26E+02	3.97E+05
HH Particulate	kg PM2.5 eq	2.13E+03	9.01E+01	3.36E+04	4.64E+01	3.58E+04
Eutrophication Potential	kg N eq	5.33E+02	9.83E+01	4.23E+03	2.82E+01	4.89E+03
Ozone Depletion Potential	kg CFC-11 eq	9.95E-03	4.77E-04	2.86E-04	2.25E-06	1.07E-02
Smog Potential	kg O3 eq	6.64E+04	4.08E+04	1.58E+06	1.46E+04	1.70E+06
Total Primary Energy	MJ	1.34E+07	1.96E+06	7.80E+08	7.55E+05	7.96E+08
Non-Renewable Energy	MJ	1.33E+07	1.95E+06	7.72E+08	7.52E+05	7.88E+08
Fossil Fuel Consumption	MJ	1.10E+07	1.91E+06	7.27E+08	7.40E+05	7.41E+08

Modeling: Part Two

Athena also allows users to develop a model with only one assembly or materials. To better understand the direct LCA measures of roofs, two models of a white roof and a green roof are developed. These two models are used to compare the LCA measures only from materials, construction, maintenance and replacing, and end of life. Impacts from operational energy use are not included.

Table 3-10. LCA Measures of a White Roof

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2, B4 & B6)	END OF LIFE (C1 to C4)	TOTAL EFFECTS
LCA Measures	Unit	Total	Total	Total	Total	A to C
Global Warming Potential	kg CO2 eq	4.13E+04	2.98E+03	2.27E+04	1.30E+02	6.71E+04
Acidification Potential	kg SO2 eq	2.83E+02	2.55E+01	2.04E+02	1.25E+00	5.15E+02
HH Particulate	kg PM2.5 eq	2.17E+01	1.39E+00	2.07E+01	6.94E-02	4.39E+01
Eutrophication Potential	kg N eq	9.84E+00	1.30E+00	8.38E+00	7.80E-02	1.96E+01
Ozone Depletion Potential	kg CFC-11 eq	1.16E-04	1.23E-06	1.75E-04	4.55E-09	2.92E-04
Smog Potential	kg O3 eq	2.84E+03	6.38E+02	1.33E+03	3.95E+01	4.85E+03
Total Primary Energy	MJ	1.07E+06	5.29E+04	8.63E+05	1.90E+03	1.99E+06
Non-Renewable Energy	MJ	1.07E+06	5.28E+04	8.61E+05	1.90E+03	1.99E+06
Fossil Fuel Consumption	MJ	1.06E+06	5.26E+04	8.49E+05	1.90E+03	1.96E+06

Table 3-11. LCA Measures of a Green Roof

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2, B4 & B6)	END OF LIFE (C1 to C4)	TOTAL EFFECTS
LCA Measures	Unit	Total	Total	Total	Total	A to C
Global Warming Potential	kg CO2 eq	1.31E+05	7.51E+03	3.62E+04	1.45E+03	1.76E+05
Acidification Potential	kg SO2 eq	8.44E+02	7.58E+01	3.82E+02	1.39E+01	1.31E+03
HH Particulate	kg PM2.5 eq	4.98E+01	4.04E+00	3.40E+01	7.70E-01	8.86E+01
Eutrophication Potential	kg N eq	2.87E+01	4.28E+00	1.13E+01	8.65E-01	4.51E+01
Ozone Depletion Potential	kg CFC-11 eq	2.43E-04	1.59E-06	1.86E-04	5.04E-08	4.31E-04
Smog Potential	kg O3 eq	1.07E+04	2.16E+03	2.31E+03	4.38E+02	1.56E+04
Total Primary Energy	MJ	2.75E+06	1.25E+05	1.42E+06	2.11E+04	4.32E+06
Non-Renewable Energy	MJ	2.74E+06	1.25E+05	1.42E+06	2.11E+04	4.30E+06
Fossil Fuel Consumption	MJ	2.47E+06	1.22E+05	1.28E+06	2.10E+04	3.89E+06

The results show that the environmental impacts of a green roof are all greater that those of a white roof through production process, construction process, use stage (operational energy use is not included) and end-of-life stage.

CHAPTER 4
RESULTS

Cost-Benefits Analysis

The results show that a green roof is less cost-effective than a conventional white roof due to its higher initial cost and maintenance cost. Compared with a conventional white roof, the NPV of net saving of a green roof is about –$ 23,272 for Rinker Hall. However, it should be noted that: 1) the maintenance requirement of green roof is mostly due to the frequent visit requirement. If proper species that need less maintenance are planted, the cost of maintenance can be reduced significantly; 2) Lots of other green roof benefits are not considered in this study. For example, the plants can help improve air quality, the application of a green roof can increase the property value, the intensive green roof can provide recreation area, etc. Although it is usually hard to convert these benefits into monetary value and include them into a cost-benefit analysis, green roofs are still used widely for various purposes.

Life Cycle Assessment

By using green roof instead of conventional white roof, the difference of each environmental impact category is calculated as Table 4-1.

The results showed that the application of a green roof will slightly decrease environment impacts of global warming potential, acidification potential, HH particulate, eutrophication potential, smog potential and total primary energy consumption. However, ozone depletion potential is increased by using a green roof instead of a regular roof. The other two models of only roof assembly indicate that if the operational energy use is not considered, the LCA measures of a green roof are much greater than those of a white roof through the life cycle (Table 4-2). Compared to a white roof, the environmental impact of smog potential is the most significant one which will increase 222.33%, and the increase of ozone depletion potential is the smallest one which is 47.51%.

Table 4-1. Comparison of LCA measures between Rinker Hall with a green roof and a conventional white roof

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2, B4 & B6)	END OF LIFE (C1 to C4)	TOTAL EFFECTS	
LCA Measures	Unit	Difference	Difference	Difference	Difference	Difference	%
Global Warming Potential	kg CO_2 eq	9.01E+04	4.53E+03	-3.11E+05	1.32E+03	-2.15E+05	-0.45%
Acidification Potential	kg SO_2 eq	5.61E+02	5.04E+01	-2.53E+03	1.26E+01	-1.90E+03	-0.48%
HH Particulate	kg PM2.5 eq	2.81E+01	2.65E+00	-2.16E+02	7.00E-01	-1.84E+02	-0.51%
Eutrophication Potential	kg N eq	1.88E+01	2.98E+00	-2.63E+01	7.87E-01	-3.72E+00	-0.08%
Ozone Depletion Potential	kg CFC-11 eq	1.27E-04	3.64E-07	1.12E-05	4.59E-08	1.38E-04	1.31%
Smog Potential	kg O_3 eq	7.89E+03	1.52E+03	-9.92E+03	3.99E+02	-1.02E+02	-0.01%
Total Primary Energy	MJ	1.68E+06	7.18E+04	-4.84E+06	1.92E+04	-3.07E+06	-0.38%
Non-Renewable Energy	MJ	1.67E+06	7.17E+04	-4.79E+06	1.92E+04	-3.03E+06	-0.38%
Fossil Fuel Consumption	MJ	1.42E+06	6.95E+04	-4.61E+06	1.91E+04	-3.10E+06	-0.42%

(Note: the building with a white roof is used as a benchmark model in this table.)

Table 4-2. Comparison of LCA measures between a green roof and a conventional roof.

		PRODUCT (A1 to A3)	CONSTRUCTION PROCESS (A4 & A5)	USE (B2, B4 & B6)	END OF LIFE (C1 to C4)	TOTAL EFFECTS	
LCA Measures	Unit	Difference	Difference	Difference	Difference	Difference	%
Global Warming Potential	kg CO2 eq	9.01E+04	4.53E+03	1.35E+04	1.31E+03	1.09E+05	163.14%
Acidification Potential	kg SO2 eq	5.60E+02	5.03E+01	1.77E+02	1.26E+01	8.00E+02	155.56%
HH Particulate	kg PM2.5 eq	2.80E+01	2.64E+00	1.33E+01	7.00E-01	4.46E+01	101.66%
Eutrophication Potential	kg N eq	1.88E+01	2.98E+00	2.90E+00	7.87E-01	2.55E+01	130.08%
Ozone Depletion Potential	kg CFC-11 eq	1.27E-04	3.63E-07	1.15E-05	4.59E-08	1.39E-04	47.51%
Smog Potential	kg O3 eq	7.89E+03	1.52E+03	9.79E+02	3.99E+02	1.08E+04	222.33%
Total Primary Energy	MJ	1.68E+06	7.17E+04	5.57E+05	1.92E+04	2.33E+06	116.97%
Non-Renewable Energy	MJ	1.67E+06	7.17E+04	5.54E+05	1.92E+04	2.31E+06	116.33%
Fossil Fuel Consumption	MJ	1.41E+06	6.95E+04	4.27E+05	1.91E+04	1.93E+06	98.25%

(Note: the white roof model is used as a benchmark model in this table.)

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

Conclusions

Green roof has a lot of environmental benefits and social benefits. The two most significant benefits are stormwater management benefit and reduce operating energy consumption. These two aspects also have been studied the most widely recent years. Previous research on runoff reduction effect of Perry yard determined that the growth media and the plants can retain 41% of the rainfall during "wet season", 34% of rainfall during winter, and 94% during spring. Two energy models through eQuest are created in this study to find the effect of white roof and green roof on operating energy consumption. The results showed that by applying a green roof instead of white roof in Gainesville, FL, the energy required for both heating and cooling can be reduced by 0.72% annually. Generally, the service life of a green roof is twice as much as that of a conventional roof. In this study, the cost-benefit analysis, which is based on a 50-year cycle, demonstrate that the net saving of a green roof is negative compared with a conventional roof due to its high initial cost and maintenance cost. Although the other benefits such as air quality improvement, Urban Heat Island Effect mitigation, increased property value, recreation area, public education effect, etc. are not studied widely, these benefits are critical when considering a green roof, especially when the owner is not cost-conscious.

To find out the influence of a green roof on the building's life cycle environment impacts, Athena Impact Estimator for Buildings is used in this study as a LCA software. Two models of Rinker Hall with a green roof and a white roof are developed in Athena. The results show that the use of a green roof on top of Rinker Hall will reduce more environmental impacts on global warming potential, acidification potential, HH particulate, and total primary energy. However, the ozone depletion potential is increased. All the changes are around 1% and this makes the LCA impacts insignificant in this study.

Limitations

The energy saving by using a green roof instead of conventional white roof is simulated through building energy model in eQuest. eQuest allows users to upload local weather file and calculate the energy consumption specifically. The result in another location may differ significantly. The type of building also affects the energy saving results. As the percentage of roof area increases out of the total enclosure surface, the effect on energy saving would be greater. In the cost-benefit analysis, only stormwater management benefit and energy saving are involved. The result shows that the green roof would be much less cost-effective than a typical roof. Although that lots of social benefits provided by a green roof are realized by public, these benefits are usually hard to be converted into monetary value when conducting the cost-benefit analysis. The cost-benefit result of this study is far more underestimated.

The software, Athena Impact Estimator for Buildings, is used conduct life cycle assessment in this study. However, there are some limitations due to that the system boundaries and assumptions are already embedded within the software.

- the producing machines, housing workers, construction transportation systems, or other activities related to basic systems are not included in the calculations.
- Only a few sites are available in Athena's database and the impact caused due to the error is not account for.
- All products are assumed that they were manufactured in north America.
- Replacement materials will be totally the same as the original one.
- The difference will be credited if service life of a replacement material exceeds the remaining assumed life of the building.

It also should be noted that life cycle assessment is a complex process which is usually conducted by experts. Athena is a whole building, environmental life cycle based decision support tool for use by building design teams at the conceptual design stage of a project. It is a simplified tool for design teams to make more holistic and informed environmental decisions about the design and material make-up of a proposed building.

		Hour																							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Heating	WD	60	60	60	60	60	65	65	70	70	70	70	70	70	70	70	70	70	70	65	60	60	60	60	60
(°F)	Sat	60	60	60	60	60	65	65	65	65	65	65	65	65	65	65	65	60	60	60	60	60	60	60	60
	Sun	60	60	60	60	60	65	65	65	65	65	65	65	65	65	65	65	60	60	60	60	60	60	60	60
Cooling	WD	77	77	77	77	77	73	73	73	73	73	73	73	73	73	73	73	73	73	77	77	77	77	77	77
(°F)	Sat	77	77	77	77	77	73	73	73	73	73	73	73	73	73	73	73	73	73	77	77	77	77	77	77
	Sun	77	77	77	77	77	73	73	73	73	73	73	73	73	73	73	73	73	73	77	77	77	77	77	77
Lights	WD	5	5	5	5	10	20	40	70	80	85	85	85	85	85	85	85	85	80	35	10	10	10	10	10
(%)	Sat	5	5	5	5	5	10	15	25	25	25	25	25	25	25	20	20	20	15	10	10	10	10	10	10
	Sun	5	5	5	5	5	10	10	15	15	15	15	15	15	15	15	15	15	10	10	10	5	5	5	5
Equipment	WD	15	15	15	15	15	20	35	60	70	70	70	70	70	70	70	70	65	45	30	20	20	15	15	15
(%)	Sat	15	15	15	15	15	15	15	20	25	25	25	25	25	25	20	20	20	15	15	15	15	15	15	15
	Sun	15	15	15	15	15	15	15	20	20	20	20	20	20	20	20	20	20	15	15	15	15	15	15	15
Fans	WD	off	off	off	off	off	on	on	on	on	on	on	on	on	on	on	on	on	on	on	on	off	off	off	off
	Sat	off	off	off	off	on	on	on	on	on	on	on	on	on	on	on	off	off	off	off	off	off	off	off	off
	Sun	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off
Infiltration	WD	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100
(%)	Sat	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100
	Sun	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
People	WD	0	0	0	0	5	10	25	65	65	65	65	60	60	65	65	65	65	40	25	10	5	5	5	0
(%)	Sat	0	0	0	0	0	0	5	15	15	15	15	15	15	15	15	15	15	5	5	5	0	0	0	0
	Sun	0	0	0	0	0	0	0	10	10	10	10	10	10	10	10	10	10	10	10	10	0	0	0	0
Hot water	WD	0	0	0	0	10	10	50	50	50	50	70	90	90	50	50	70	50	50	50	10	10	10	10	0
(%)	Sat	0	0	0	0	0	0	10	20	20	20	20	20	20	20	20	20	20	10	10	10	0	0	0	0
	Sun	0	0	0	0	0	0	0	10	10	10	10	10	10	10	10	10	10	10	10	10	0	0	0	0

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BIOGRAPHICAL SKETCH

Lan Yao graduated from Xiamen University in China, with a Bachelor of Civil Engineering. She started graduate studies at the University of Florida in 2015. She has pursued her Master of Science in Construction Management with a concentration in sustainable construction.