Green Roof Development in Urban Areas

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21 July 2017
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Abstract— **Features of urban environments, such as high population density and a lack of green spaces, are linked to environmental problems such as excessive heat absorption, polluted stormwater runoff, and comparatively high energy consumption. One potential method for mitigating the negative effects of these issues is by implementing energy-saving roof designs. Green roofs are layered structures that consist of vegetation, engineered soil, and various water management materials. In this study, a green roof is virtually retrofitted to a building that models a typical office space found in Manhattan's East Midtown business district to introduce a method to reduce energy costs. The design process involves an analysis of materials used to construct the green roof and the use of AutoCAD to render a two-dimensional plan of the roof. Calculations based on similar studies suggest that the implementation of this green roof could reduce building energy consumption by 35%. Furthermore, the amount of money saved by limiting use of temperature regulation equipment would likely compensate for the construction cost within one to two years of operating at maximum productivity.**

I. INTRODUCTION

The scientific community is at near consensus that over the past 150 years, humans have constructed society a way that has inadvertently fared poorly for the environment. Issues unique to this century, including the effects of phenomena such as climate change, widespread deforestation, and the pollution of waterways, appear to have no clear, all-encompassing solution. This has left the question open as to how to stop or slow environmental deterioration. It is no longer a viable option to deliberate on solutions; by World Health Organization estimates, 250,000 climate change-related deaths per year are expected between 2030 and 2050 [1]. Progress towards environmentally conscious infrastructure generally takes two forms; destroying and rebuilding, or renovating existing infrastructure to be more efficient. In Western Europe, these ideas have manifested into a transition to renewable energy sources, like solar energy. In Germany, the solar cell market has seen an annual growth rate of approximately 31% for the last decade, while simultaneously phasing out reliance on fossil fuels, which has comprised the global energy sector's bulk for the preceding centuries [2]. Other European countries have similarly restructured their infrastructure goals in the face of so-called "green consciousness" [3]. In the United States, however, distinct political pressures have slowed environmental progress significantly, due to accusations of economic inviability and the disruption of the country's individual labor demographics. Some of these concerns are valid, as many projects often involve major long-term construction, require massive amounts of funding, and are unfeasible on a larger scale. Thus, improving current systems to be more efficient is often a more desirable path, due to its reduced costs. Reconciling profit with environmentalism may prove to be the defining challenge in the coming years. One innovation that has achieved this feat is the "green roof," or the placement of vegetation and its growing medium on the roof of a building.

Green roofs serve a diverse range of purposes that play to a variety of needs ranging from aesthetic improvement to financial benefit. These rooftop ecosystems are generally sorted into two categories based on soil depth. Intensive roofs generally have a substrate layer with a thickness greater than six inches, while extensive green roofs typically have a depth ranging from three to six inches. Thus, intensive green roofs are heavier, more complex systems that often double as gardens or public spaces. Because the rooftop vegetation has deep roots and a demand for water and maintenance, intensive green roofs are generally integrated into a building's design before construction begins. Existing buildings can be retrofitted for extensive green roofs, which accounts for their versatility and universal applicability, in contrast to intensive roofs. They serve a more utilitarian purpose, and their primary objective is to reduce energy usage, not to contribute aesthetic value to a roof. This paper will primarily focus on the benefits offered by extensive green roofs, since they more effectively contribute to energy saving efforts and general environmental stewardship than intensive green roofs. These advantages address a number of the environmental problems previously outlined, such as waterway pollution and rising temperatures.

The mitigation of these issues is achieved through stormwater runoff management and thermal reflectivity. To determine the effect of green roofs on energy conservation in an existing building, a hypothetical green roof was installed on a model building in the Midtown East neighborhood of New York City, which has remarkably outdated and aging infrastructure. This study was conducted for the purpose of analyzing the real-life implications of green roof technology for the future of green development.

II. Background

A. Green Roof Mechanisms of Action

Green roofs' benefits include the management of temperature fluctuations, stormwater retention, and reduction of greenhouse gases in the atmosphere. Different components of the roof operate to produce each of these effects.

The presence of a growth medium, vegetation, and water in a green roof regulate heat transfer in buildings more effectively than bare roofs. Soil and plant matter have low thermal conductivities, meaning that heat flows slowly through them to reach the structural roof, thereby lessening the effect on the internal temperature of the roof. Any water stored in the soil further slows heat absorption into the building due to its high heat capacity, which refers to the amount of energy required to change the temperature by 1°C [4]. These mechanisms manage building temperature throughout the year, keeping buildings cooler in summer and warmer in winter.

Heat fluctuations in summer are also reduced through the combination of evaporation and evapotranspiration. Heat from the air is used to evaporate the water, which cools the air. Evapotranspiration refers to a process plants use to release water back into the air. Plants release liquid water through their leaves, which then evaporates. This process cools the air similarly to how regular evaporation does, by taking heat from the environment to change the phase of water [5]. The presence of plant coverage on green roofs produces a high rate of evapotranspiration. These processes together control heat fluctuation effectively. According to a 2001 study, a difference of 10°C was observed between the roofs of non-insulated buildings with and without green roofs, which illustrates the cooling power of this technology [6].

Stormwater is processed and retained in the vegetation and specialized layers of the green roof. During photosynthesis, plants take up water for the production of glucose. Water in soil deposited by rain and snowfall travels through the plant's roots and stem, which are natural filters. This is advantageous in cities, where stormwater runoff can introduce pollutants to waterways and render them toxic. Furthermore, water storage from absorbent plants in green roofs can prevent overflow and eventual flooding. Water also evaporates faster in green roofs than on bare roofs when plants use it, resulting in a reduction of the standing water load after rainfall and preventing potential roof collapse. Finally, green roofs remove carbon dioxide (CO_2), a greenhouse gas, from the atmosphere during photosynthesis. CO_2 contributes to global warming by preventing the reflection of solar radiation, keeping heat in the atmosphere.

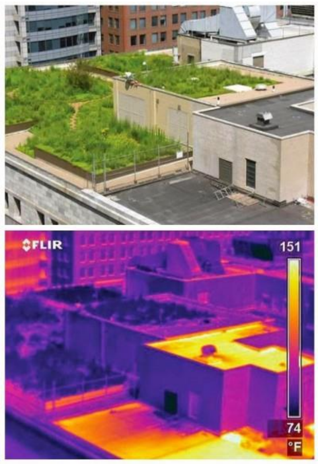

Fig. 1 Thermal imaging exhibiting temperature difference of two adjacent roofs with and without vegetation [7].

Plants purify the air and store carbon dioxide in a process called carbon sequestration [8]. Over time, this reduces the concentration of carbon in the air.

B. Structural Properties of Buildings

Contractors wishing to start a construction project in a given area are required to adhere to building codes issued by the pertinent local government. These codes define the standards that must be met for the building to get approval. In order to maintain a dimension of realism in the study, outdated New York City building code from 1938 is used to generate the dimensions and structural characteristics of the building, such as loading capacities and ventilation systems. The dead load of a building is defined in the 1938 code as "includ[ing] the weight of walls, permanent partitions, framing, floors, roofs, columns and their fireproofing, and all other permanent stationary construction entering into a structure" [9]. This definition will be used when analyzing the weight limit per sq. foot of the green roof, as exceeding a building's maximum dead load would, over time, degrade the integrity of the structure and ultimately stress it to the point of ineffectuality.

In order to determine the force exerted by the green roof on the structural roof due to gravity, Newton's Second Law,

$$(1) \quad F=ma$$

is used, in which F refers to force, measured in Newtons (N), m refers to mass, measured in kilograms (kg), and a refers to acceleration, measured in m/s^2. The force of gravity is taken as 9.8 m/s^2. Newton's Third Law, which states that every action has an equal and opposite reaction, is also the basis for the load calculation; the dead load's force can match, but not exceed the roof's normal force, which is exerted upwards in the opposite direction as gravity. If the dead load exceeds the dead load capacity, the roof's integrity is degraded at an accelerated rate, leading to a potential cave-in or a shortening of the green roof's life cycle.

C. Calculation of Energy Demands

Most buildings constructed prior to the middle of the 20th century contained little to no insulation in their walls, due to the low price and accessibility of electricity. Adequate insulation, in fact, was not required in building design prior to 1965, meaning that contractors had no incentive to use it [10]. As a result, buildings from this era retain and deflect heat extremely poorly. This effect leads to significant temperature fluctuations in the absence of constant air conditioning or heating. Heating, ventilation, and air conditioning (HVAC) systems are installed depending on the needs of the building, which are usually dictated by the local climate and the total area of the building. HVAC systems are differentiated based on their tonnage, a unit that refers to the "amount of heat needed to melt one ton (2000 lbs.) of ice in a 24 hour period," or 12,000 BTU/hr [11]. In order to calculate the HVAC tonnage needed, an equation that acknowledges the number of people in the building, its square footage, and the number of windows in the space is used [12].

III. MATERIALS AND DESIGN

A. Location and Building Dimensions

One of the primary purposes of this research is to stress the universal applicability of green roofs; as such, a building in the most populous US city, New York, was chosen as the site for the green roof design. The East section of Midtown Manhattan was specifically selected as the location of the model building because it represents a region with outdated office infrastructure and high energy usage.

There are more than 15,000 properties in New York City that contain more than 50,000 sq. feet of floor space; together, they consume more than 120 trillion BTU of energy in 2013 [14]. A number of these building are located in Midtown East, such as the New York Design Center (NYDC), which the study's model building is heavily based on. The NYDC was constructed in 1926, contains 16 stories, and has served as a furniture and design showroom since its initial construction. The NYDC was chosen as the basis for the study primarily due to its age and similarity to other buildings in the area, which include shopping malls and other showrooms.

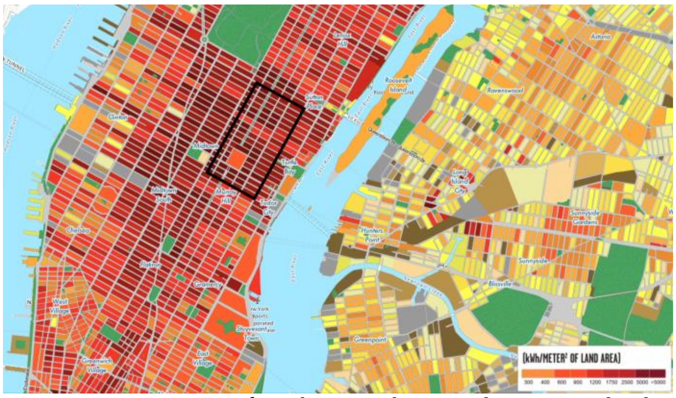

Fig. 2 Energy usage map of Manhattan, with East Midtown area outlined in black [13].

Furthermore, since this study's purpose is to reaffirm the universality of green roof technology, the decision was made to model a physically large building in a deeply urban area in order to show its applicability to other similar buildings. The average building age in this neighborhood is 70 years, meaning that many of these buildings were built before modern energy codes were established. As a result they rely heavily on HVAC units for thermal regulation. The study's model building is an uninsulated ten-story office space. The 1938 NYC Building Codes were used to approximate the minimum load required around the time when the offices were constructed and thus to determine the load the roof of this building would be capable of bearing.

B. HVAC Tonnage and Location

The HVAC system is an important factor when considering the design of a green roof. The size of an HVAC unit is dependent upon its tonnage, where one ton is equivalent to 12,000 Btu/hr. The first step in determining the size of the HVAC unit used in this study was to calculate the building's cooling load. The cooling load, measured in Btu/hr., is the amount of heat the HVAC unit must remove in order to regulate a building's temperature. This number was determined by utilizing the conversion chart provided by ENERGY STAR®, a joint program of the Environmental Protection Agency (EPA) and the Department of Energy (DOE). Using the capacity needed for a 1000 sq. foot space, 18,000 Btu/hour, and multiplying it by a factor of 200 to account for the total area of the office space to be cooled, 200,000 sq. feet, the cooling load was determined. Further calculations accounted for the number of workers in the building, which is considered an important factor in determining the amount of heat that is insulated and confined to the interior of the office space. Every person occupying the building contributed an additional 600 Btu to the capacity [15]. According to a 2008 New York City Building Code, 100 sq. feet of space is needed per occupant for business areas [16]. Therefore, the maximum occupancy for the 200,000 sq. foot building used for this green roof design is 200,000 ft^2 divided by 100 ft^2, or 2,000 people.The initial capacity disregarding the inhabitants of the building was found to be

3,600,000 Btu/hr, while the capacity solely from the occupants of the space resulted in 1,200,000 Btu/hr. With these combined factors, the building's total cooling load is 4,800,000 Btu/hr. However, due to the sheer size of the building, the amount of energy needed to heat and cool the interior was too great to be generated by a single HVAC unit on the roof of the building without compromising the integrity of the structure. For that reason, the HVAC system was modeled after those of New York City skyscrapers, such as the Empire State [17] and Chrysler Buildings [18], in which the HVAC systems are broken up into multiple units throughout the building, a technique referred to as zoning. Zoning is a beneficial method because it reduces the dead load of a roof by distributing the weight of the HVAC system instead of concentrating it in one area. Additionally, purchasing and installing smaller units has proven to be more cost effective than doing so for larger units, as well as more energy efficient, since a single large unit may produce or remove more heat than necessary, and in the process, waste money and energy [19]. For these reasons, the building the green roof is designed for is divided into five zones, with each zone comprised of two floors. In each zone, an 80 ton HVAC unit is implemented, each with a cooling capacity of 960,000 Btu/hr, calculated by multiplying 80 tons by 12,000 Btu/hr, the conversion factor for tons to Btu. These five units operate efficiently, since combined, they have a total cooling capacity of 4,800,000 Btu/hr, the precise maximum cooling load of the building. The dimensions of each unit are 14' 9" x 8' x 9' 1.5", with an area of 118 sq. feet and a weight of 11,203 lbs. Using the New York Design Center as a model for the building, the fifth HVAC unit was placed on top of the roof in order to acknowledge its presence in the green roof design and take into account its contribution to the structure's dead load.

C. *Determination of Layers*

Conventional green roofs contain a base of six layers, with additional layers inserted depending on the location's individual demands. The determining factors in selecting a number of layers includes the amount of annual rainfall and need for additional insulation. The seven layers used in this study's green roof are, from the bottom most layer, the waterproofing sheet, the root barrier, the water retention layer, the drainage layer, the filter layer, the substrate layer (soil), and the vegetation, pictured in Fig. 3. The structural roof is not considered a layer of the green roof, but rather as the foundation for the above layers. The retention layer is often not included in other green roofs, but its function is important to the green roof in this study. Its purpose is to capture any excess water and particulate matter and prevent them from the above layers from reaching and damaging the barrier layers below it. Although reasonably effective, the risk of leakage from the drainage layer is imminent due to the levels of rain and snowfall in the New York City area. The layers of a green roof should together function to provide insulation, retain and filter water, and protect the underlying structural roof. Thus, the materials that each layer is constructed from are important to optimize functionality.

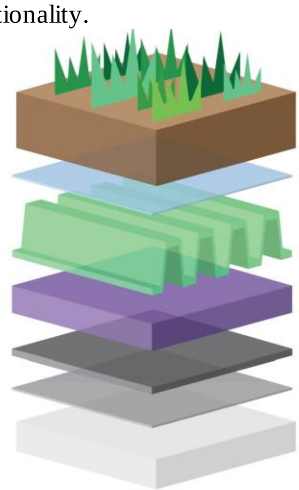

Fig. 3 The seven layers of the green roof, excluding the structural roof: (from bottom to top) waterproofing sheet, root barrier, retention sheet, drainage layer, filter layer, substrate, vegetation [20].

D. *Layer Materials*

TABLE I
LAYERS, MATERIALS, AND SPECIFICATIONS

Layer	Material	Weight (lb/ft^2)	Thickness (in)
Waterproofing	Bituminous fiberglass reinforced waterproofing membrane	0.70	0.14
Root Barrier	Polyethylene (LDPE)	0.16	0.06
Water Retention	Recycled polyester fibers	0.25	0.39
Drainage	Drain Max® 200 Series	0.15	0.25
Filter	Nonwoven polypropylene (PP)	0.02	0.02
Substrate	RoofLite® Extensive 500 Soil	18.04	3.94

The waterproofing layer protects the structural roof, which is made of concrete, from water damage. As Table 1 illustrates, the material chosen for waterproofing is a bituminous fiberglass reinforced waterproofing membrane. This consists of a sheet made of polyethylene resin. This material is a lightweight thermoplastic that would not contribute heavily to the dead load nor would it become distorted over time; additionally, the company that produces this material includes a fiberglass backbone in the composition, meaning that tears and rips are much less likely to occur.

Root barriers can either be characterized as a chemical treatment or a physical barrier. The use of copper based products can often prohibit root growth past the desired depth, but over time the concentration decreases and thus efficacy goes down [21]. Physical barriers increase the lifespan of the green roof, making them more desirable despite the additional weight. The two common materials used as the root barrier are PVC and polyethylene (LDPE). However, based on environmental impact calculations recorded in the study referenced by [22], it was determined that LDPE universally outperformed PVC by being more sustainably sourced while maintaining similar functionality. Furthermore, LDPE is lighter, making it the material of choice as the root barrier.

The retention layer is important to stop any water from reaching the previous layers. Recycled textile fibers, which come in polyester mattresses, contain reused materials that are minimally destructive to the environment and display high absorptive abilities. These qualities make it a suitable material for use in the retention layer. This material does not contribute greatly to the dead load, but can absorb leakage from the drainage layer effectively.

The drainage layer serves to hold water that flows through the above layers. The Drain Max® 200 Series of drainage cups is composed of a polystyrene (HIPS) core and a polypropylene (PP) filter layer. Both of these materials are extremely durable, lightweight thermoplastics. Polymers like HIPS and PP are reliable in green roofs due to their flexibility, durability, and tensile strength [21]. Furthermore, the company that makes this product ensures that at least 70% of the materials used in production are recycled, decreasing waste in production.

The filter layer's purpose is to stop any small particles from permeating through to the drainage layer from the substrate layer. As such, it is necessary that the material used has small pores to allow only water through. According to previous research models, polymeric fibers are most commonly used in the filter layer, such as polypropylene. The PP used in the filter layer is produced as a nonwoven geotextile for easy installation. PP is not susceptible to water distortion or degradation, allowing it to work efficiently in the filter layer. These resistant characteristics are derived from its classification as a thermoplastic.

The substrate layer consists of the soil medium in which the vegetation will grow. Across green roofs, materials used in this layer vary greatly, depending on accessibility of materials, weight restrictions, and accompanying vegetation. In a 2005 study conducted by Chenani et al., two substrate mixes, one made of clay, brick and compost, and another made of sand and pumice, were tested for their efficiency [22]. Compost is a commonly used material in this layer due to its universal accessibility, high nutrient density, and recycled properties. Although the other materials, such as the aforementioned pumice and sand, analyzed in this study contributed positively to plant growth and insulation, it was determined that the aggregate weight would overload the roof's dead load capacity, making it an unsuitable option in the roof. Mineral content is furthermore an important component in the substrate, as healthy plant growth necessitates availability of minerals like phosphorus, potassium, and magnesium [23]. Some research models include substances like quarry fines, ash, and waste clay in their substrate to provide these nutrients, which are all recycled materials [24]. Commercial producers of green-roof-specific soil sell "lightweight" mixes, which are especially porous while remaining nutrient dense. Rooflite® Extensive 500 soil is a mix of mineral aggregates and organic materials, which includes compost and substances like Potassium Chloride and Calcium Chloride. It was chosen as the substrate layer because it includes recycled materials and is relatively lightweight, making it both environmentally favorable and efficient in the layer.

E. Vegetation

Extensive green roofs have a shallow growth medium, meaning the vegetation will be subject to harsh conditions, including fluctuations in water availability and temperature [25]. Species that are able to tolerate these stresses must be selected in order to ensure that the roof performs at its maximum productivity. For example, in order to regulate runoff, the roof must be able to efficiently absorb and release stormwater.

1) *Biodiversity:* While individual species may optimize a single function, combinations of different plant groups are able to demonstrate a greater range of abilities [26]. Structural diversity found in a species-rich green roof allows different plants to provide complementary functions. Using a diverse array of taxonomic groups additionally limits the plants' competition for the same resources.

The three types of plants that have been selected for this green roof design are succulents, creeping shrubs, and tall forbs. Sedum, which are all succulents, are often planted on extensive green roofs because they use crassulacean acid metabolism (CAM) photosynthesis. In this process, transpiration water loss is minimized by limiting the opening of the stomata to at night, when less water will be evaporated [27]. Shrubs and forbs are additionally well-suited for green roofs as a result of their drought avoidance and low transpiration rates [28]. The species used in this design are *Empetrum nigrum, Gaultheria procumbens, Vaccinium vitis-idaea* (creeping shrubs), *Campanula rotundifolia, Plantago maritima, Solidago bicolor* (tall forbs), *Sedum acre, Rhodiola rosea*, and *Sedum spurium* (succulents).

Fig. 4 A *Sedum spurium* plant [29].

2) *Literature Review:* The selection of individual species was determined by using studies that compared the performance of various plant types on the same roof in order to ensure that variation in vegetation is the only changing variable affecting roof performance. [26] fulfilled this role by investigating the performance of twenty-nine combinations of thirteen plant species on a green roof in Halifax, Nova Scotia. This paper was the central resource for determining plant species because it provides analysis of different plant type combinations and quantifies roof performance in a variety of categories particularly relevant to the goals of this green roof design.

Variations in technical specifications for the green roof, including differences in layer properties and the surrounding environment, can have significant effects on the performance of vegetation. Although distinctions exist between the theoretical roof proposed in this paper and that were tested in [26], these dissimilar conditions will not likely have a significant effect on the efficiency of the roof. One notable difference is that the substrate thickness proposed in this green roof design is 3.94 inches (10 cm), while [26] uses a 2.36 inches (6 cm) thick growth medium. However, Getter et al.'s 2009 study on sedum growth in a Michigan green roof found the performance of plots with substrate depths of 7.0 and 10.0 cm to be "statistically the same" [30]. These findings imply that differences in green roof setup will not have a significant impact on the applicability of [26]'s findings to this design. Because there are minimal climate differences between Manhattan and Halifax, Nova Scotia, the species studied in [26] paper will likely perform similarly if implemented in this theoretical green roof. Average annual temperatures for New York are comparable to the temperature range of Halifax when the study was conducted. [26] states that the average monthly air temperature during the four-month study was 50.36 to 66.92º F, while the New York City annual low and high temperatures were 48 and 62.3ºF in 2016 [26][31]. The average annual total rainfall is also similar in the two locations, found to be 49.27 inches in Halifax and 42.17 inches in Manhattan [32][33]. Because the climates in the two regions are comparable, there will likely be few problems associated with using the same species as the Nova Scotian study on a New York green roof.

3) *Habitat Template and Native Species:* To increase biodiversity and identify species well-suited for survival on green roofs, [34] examined plant communities in natural habitats that involve conditions and stresses that are similar to rooftop environments in order to determine the thirteen species to test. Though the thirteen species in the 2010 study were originally chosen because they are native to Nova Scotia, all but three of the plants that have been selected for use in this green roof design are additionally native to New York state [35]. The fact they are native implies the plants may be adapted for survival in the Manhattan climate [36]. [26] was used to determine the specific plant species to use on the theoretical green roof to ensure both that they are resistant to the stresses such an environment presents, while also being able to grow in the same plot without compromising their abilities to perform their functions.

4) *Determining Plant Selection:* The group of three plant types used in this green roof design was selected because it was within the ten top-performing groupings of the 29 [26] examined. There were two groups with nearly identical high performance, both of which contained tall forbs and succulents. However, one included creeping shrubs while the other used grasses. Two factors led to the selection of the creeping shrub group. The primary reason was that grass, when dry, presents a greater fire hazard than creeping shrubs. The only other distinguishing factor was the Aboveground Biomass Index, which measures the amount of plant growth above the soil level. Though a high biomass index is typically preferred, the fact that the group performed well regardless of aggregate biomass indicates that this factor did not negatively affect plant performance. In order to reduce the dead load on the roof and eliminate a possible fire risk, the group consisting of creeping shrubs, tall forbs, and succulents was selected.

Fig. 5 A green roof in Philadelphia planted with *Sedum spurium* [37].

F. Installation and Maintenance

After the materials for each layer of the green roof were selected, the installation process was researched in order to obtain reasonable estimates regarding the amount of time and number of workers needed to complete the project. Two phone calls were made to New York green roof contractors, the first to New York Green Roofs and the second to Eco Brooklyn Green Builders, both full service green roofing firms.

The data collected from these conversations provided that it would take 10 construction workers about a month to complete the installation process for a ten story, 200,000 sq. foot building in the East section of Midtown Manhattan. Then, the median hourly wage of a New York construction worker, adjusted for the 10 workers, was used to estimate the cost of installation [38].

Subsequent research was done on maintenance fees after the completion of the roof. Maintenance during the establishment period, or the first year after the finalization of the green roof, is especially important. Inspecting soil, distributing excess cuttings, and weeding are key aspects of maintenance that ensure that the green roof will operate at full capacity. According to the General Services Administration Government agency, it is recommended that at least 3 maintenance visits are conducted by two construction workers during the establishment period of an extensive green roof [39]. Using this information, cost for maintenance over the life cycle of the green roof was taken into account when calculating the final cost of the project.

G. AutoCAD Rendering

After determining the dimensions of the structural roof and HVAC system, the computer program AutoCAD was used to render a two dimensional image of the building with the green roof installed. The finished drawing has eight layers, dedicated to the structural roof, water management, electrical appliances and systems, plumbing, stairs, vegetation, annotations, and dimensions.

Fig. 6 represents an aerial view of the roof; the areas labelled as "vegetation" are representative of the entire green roof, since the top layer is the only visible layer from this frame of reference.

During the design stage of the study, decisions regarding the width and placement of the stairs, drains, and gutters were made, along with how the actual plots of green roof would be designed. A spiral design was chosen for the stairs in order to evade the construction that accompanies a straight staircase.

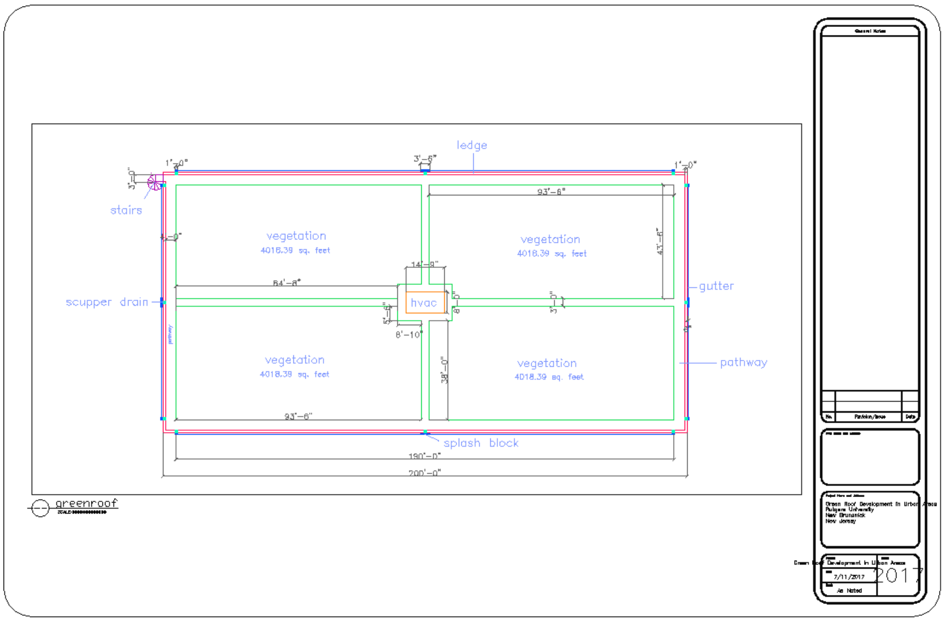

Fig. 6 Aerial view of green roof rendered in AutoCAD.

The dimensions of the staircase width were determined based on the approximate number of people that would use it in case of emergency. The width requirement, set forth by New York City building code 1005, is 0.3 inches for each occupant served [40]. Since extensive roofs require little maintenance, this number would likely be under 100, giving a minimum width of 30 inches. For additional safety precaution, the width of the staircase is three feet. The water management and plumbing systems refer to the combination of gutters and drains. The gutter width, six inches, was determined by the square footage of the roof, slant angle of the roof, and number of downspouts. City building codes require at least a six inches diameter gutter for a roof of the building's size, which Fig. 6 illustrates [41]. Scupper drains, pictured in Fig. 7, are both aesthetically beneficial and allow for direct drainage from the roof. Furthermore, they allow for a continuous ledge around the roof, which is required to be 42 inches in height according to 2014 NYC building codes [42]. The paths between and around the green roof quadrants were placed to allow for maintenance of the green roof and access to the rooftop HVAC system. Dividing the green roof into four sections that are equal in area is the most efficient use of space to maximize green roof coverage while allowing for maintenance and observation.

Fig. 7 A typical scupper drain, which is installed at the junction of the roof ledge and structural roof [43].

IV. Results and Discussion

The final calculations for this study reveal important implications of green roof design. Utilizing data from previous studies and applying this research to the dimensions of the design rendered on AutoCAD, the area, depth, weight, and cost of the green roof were found. First, the area of each section of the roof was calculated. Keeping in mind constant values such as the area of the HVAC unit, 118 sq. feet, and regulation sizes for maintenance pathways, 5 feet wide for perimeter pathways and 3 feet wide for inner pathways, the remaining space was optimized to serve as plots for vegetation. The area of each plot was found to be 4018.66 ft^2. Therefore, a total of 16,074.64 sq. feet is provided between the four plots for vegetation to grow. These calculations were crucial in determining other aspects of the green roof, such as weight and cost later on.

Next, the depth of each individual material that comprises the seven layers of the roof was recorded, displayed in Table 1. Combined, the total depth of the roof is 4.85 inches. Furthermore, although the species differ, the average expected plant height is 6.35 inches, giving the roof a total depth of roughly 11.2 inches. Since extensive roofs are typically six inches or less in thickness, sans vegetation, this design accurately represents an ideal extensive green roof.

Finally, the weight of the green roof contributes to the dead load by exerting a downward force onto the structural roof. Therefore, the primary step regarding the weight calculations of this design was to determine the load capacity of the roof. A typical commercial roof from the time period that the building was modelled after, the late 1930s, can support 40 lbs/ft^2 [44]. Using equation (1), the load capacity of the roof was determined by multiplying the area of the space, 20,000 sq. feet, by the mass, 40 lbs/sq. feet, in order to obtain a final capacity of 800,000 lbs, or 3558.58 kilonewtons (kN) of force.

After the load capacity was determined, the weight of the roof was calculated. Using equation (1), the total force applied by the dead load of the roof was calculated by multiplying the weight of each layer in lbs/sq. feet, recorded in Table 1, by the amount of material needed, recorded in Table 2. Besides the components that make up the green roof itself, aspects of the dead load include the HVAC unit, weighing 11,203 lbs, and the gravel used to line the maintenance pathways, which weighs 22.2 lbs/sq. foot, multiplied by the area of the pathways, 3808.28 sq. feet, amassing 84,629.50 lbs. Combining these values, the force contributed by the dead load is 2382.57 kN. Similarly, the force exerted by the live load was determined, this time accounting for the weight of temporary factors such as water retention from rain and snow, and people who may be on the roof for maintenance purposes. The average snowfall in Manhattan is 2.26 inches, or .19 feet [45]. Using this statistic and multiplying it by the density of snow, 3.12 lb/cubic feet, and the area of the roof, 20,000 sq. feet, the snow load is 11,856 lbs. Similarly, the weight accounting for water retention within the layers was calculated using the retention capacity for the materials, 8.32 lbs/sq. feet, and multiplying it by the area covered by the materials, 16,074.64 sq. feet, to result in an added 13,3741 lbs. Finally, utilizing the weight of an average human being, 136 lbs, and multiplying it by 10, a reasonable estimate for the maximum number of people on the roof at any given time, the weight contributed by personnel is 1,360 lbs [46]. By adding these figures, the aggregate force contributed by the live load equates to 653.74 kN, resulting in a total of 3036.31 kN of force applied by both the dead and live load. Because this number is less than the total load capacity previously stated, it is assured that the structural roof can support the weight of the green roof.

TABLE II
INDIVIDUAL COST CONTRIBUTIONS

Layer	Amount of Material (sq. feet)	Cost per sq. foot	Total Cost Contribution
Waterproofing	20,000	$0.33	$6,600
Root Barrier	16,074.64	$0.21	$3,375.67
Water Retention	16,074.64	$0.05	$803.73
Drainage	16,074.64	$0.43	$6,912.10
Filter	16,074.64	$0.07	$1,125.22
Substrate	16,074.64	$1.59	$25,630
Vegetation	16,074.64	$0.78	$12,538.22
Gravel	3,808.28	$1.93	$7,349.98

The final calculation for this study was to analyze the total cost of the green roof design. By adding the cost for each component of the roof, displayed in Table 2, with the installation price, the aggregate cost was found. The cost for materials and plants was found by adding up the total cost contribution for each aspect of the roof. Then, the cost for installation was calculated by multiplying the median hourly wage of a New York construction worker, $18.68/hour, by the time for installation, roughly 164.8 hours, and then by 10 to account for the number of workers [38]. Adding these two values together, the aggregate cost was found to be $98,064, with an additional $7,200 per year in maintenance fees. This price was then compared to the annual energy savings to determine how long it would take for the roof to become profitable. According to the Madison Gas and Electric Company's 2010 report, U.S. commercial office buildings annually consume an average of 17.3 kilowatt-hours (kWh) at $0.20 in energy and 31.8 cubic feet of natural gas per sq. foot at $0.98 per 100 cubic feet of gas [47]. Using this statistic, it was determined that the building before the installation of the green roof spent $692,000 towards all electricity demands, 28% ($193,760) of that cost accounting for spendings on HVAC systemusage. 6,360,000 cubic feet of natural gas would be used in the building, costing $62328. Space heating accounts for 86% ($54,462) of natural gas usage. Estimates show that energy savings between 10 and 50 percent can be expected to result from green roof implementation on uninsulated buildings. Given office buildings' high spending on heating and cooling systems, a 35% reduction in energy consumption would mean $86,878 savings each year [48]. Thus, the energy savings caused by the green roof would surpass the initial investment for installation within the first two years of operating at full capacity with fully grown plants.

V. Conclusion

The results of this study show that a fully functional extensive green roof could be retrofitted to a building in NYC's East Midtown neighborhood for $98,064. The construction period would last approximately one month, and if planted in early spring, the vegetation would reach maturity by summer. At maximum productivity, the green roof would save $86,878 in energy spending per year, based on a conservative estimate. Thus, the amount of money saved by the roof would exceed the installation cost within two years. The expedient and non-invasive nature of the green roof's construction supports the argument for expanded green roof infrastructure across the United States and around the world. A universal reduction in energy consumption would reduce the amount of coal and natural gas extracted and burned. Green roof technology, if implemented on a large scale, would reduce reliance on nonrenewable energy and stave off the effects of climate change in the long term.

Acknowledgments

The authors of this paper would like to acknowledge and thank those who aided them throughout the duration of this project, specifically their Residential Teaching Assistant and project mentor Alissa Persad. Additionally, they extend their thanks to the individuals and organizations who sponsor and provide support for the Governor's School of Engineering and Technology, namely Dean Jean Patrick Antoine, Dean Ilene Rosen, Rutgers the State University of NJ, Rutgers School of Engineering, the State of New Jersey, Lockheed Martin, Silverline Windows, and all of the New Jersey Governor's School of Engineering and Technology Alumni. Without their contributions, this research opportunity would not have been possible.

References

[1] "Climate change and health," *World Health Organization*. [Online]. Available: http://www.who.int/mediacentre/factsheets/fs266/en/. [Accessed: 15-Jul-2017].

[2] O. Morton, "Solar energy: Silicon Valley sunrise," *Nature*, vol. 443, no. 7107, pp. 19–22, Jul. 2006.

[3] J. Caputi, "Green Consciousness," *Ethics & the Environment*, 15-Nov-2007. [Online]. Available: https://muse.jhu.edu/article/223981. [Accessed: 15-Jul-2017].

[4] D. Becker and D. Wang, "Green Roof Heat Transfer and Thermal Performance Analysis," 2011.

[5] "Using Trees and Vegetation to Reduce Heat Islands," *EPA*, 12-Aug-2016. [Online]. Available: https://www.epa.gov/heat-islands/using-trees-and-vegetation-reduce-heat-islands. [Accessed: 15-Jul-2017].

[6] A. Niachou, K. Papakonstantinou, M. Santamouris, A. Tsangrassoulis, and G. Mihalakakou, "Analysis of the green roof thermal properties and investigation of its energy performance," *Energy and Buildings*, vol. 33, no. 7, pp. 719–729, 2001.

[7] "Reducing Urban Heat Islands: Compendium of Strategies," 2008.

[8] "Carbon Sequestration," *Carbon Sequestration - Forest carbon basics - Carbon - Northern Institute of Applied Climate Science (NIACS) - Northern Research Station - USDA Forest Service*. [Online]. Available: https://www.nrs.fs.fed.us/niacs/carbon/forests/carbon_sequestration/. [Accessed: 15-Jul-2017].

[9] "1938 Building Code - Article 2," *Welcome to NYC.gov*. [Online]. Available: https://www1.nyc.gov/. [Accessed: 15-Jul-2017].

[10] H. Castleton, V. Stovin, S. Beck, and J. Davison, "Green roofs; building energy savings and the potential for retrofit," *Energy and Buildings*, vol. 42, no. 10, pp. 1582–1591, 2010.

[11] "What's a "Ton" in the HVAC World." [Online]. [Accessed: 15-Jul-2017].

[12] "How to Size a Commercial Air Conditioner," *Sobieski*, 13-Sep-2016. [Online]. Available: http://www.sobieskiinc.com/blog/how-size-commercial-air-conditioner. [Accessed: 15-Jul-2017].

[13] Estimated Total Annual Building Energy Consumption at the Block and Lot Level for New York City. [Online]. Available: http://qsel.columbia.edu/nycenergy/. [Accessed: 15-Jul-2017].

[14] "NEW YORK CITY'S ENERGY AND WATER USE 2013 REPORT." [Online].

[15] "Room Air Conditioner," Energy Star. [Online]. Available: https://www.energystar.gov/products/heating_cooling/air_conditioning_room?qt-consumers_product_tab=2#qt-consumers_product_tab. [Accessed: 19-Jul-2017].

[16] "Chapter 10: Means of Egress," 2008. [Online]. Available: http://www2.iccsafe.org/states/newyorkcity/Building/PDFs/Chapter%2010_Means%20of%20Egress.pdf. [Accessed: 15-Jul-2017].

[17] "The Empire State Building." [Online].

[18] "Solutions," *Regal Beloit | Solutions*. [Online]. Available: https://www.regalbeloit.com/Solutions. [Accessed: 15-Jul-2017].

[19] C. Risen, "How to Heat and Cool a Supertall," *architectmagazine.com*. [Online]. Available: http://www.architectmagazine.com/technology/how-to-heat-and-cool-a-supertall_o. [Accessed: 15-Jul-2017].

[20] "Green roofs," *Growing Green Guide*. [Online]. Available: http://www.growinggreenguide.org/technical-guide/construction-and-installation/green-roofs/. [Accessed: 19-Jul-2017].

[21] F. Bianchini and K. Hewage, "How "green" are the green roofs? Lifecycle analysis of green roof materials," *Building and Environment*, vol. 48, pp. 57–65, 2012.

[22] S. B. Chenani, S. Lehvävirta, and T. Häkkinen, "Life cycle assessment of layers of green roofs," *Journal of Cleaner Production*, vol. 90, pp. 153–162, 2002.

[23] "Mineral elements required in plant nutrition," *Mineral elements required in plant nutrition*. [Online]. Available: http://broome.soil.ncsu.edu/ssc051/Lec5.htm. [Accessed: 15-Jul-2017].

[24] C. J. Molineux, C. H. Fentiman, and A. C. Gange, "Characterising alternative recycled waste materials for use as green roof growing media in the U.K.," *Ecological Engineering*, vol. 35, no. 10, pp. 1507–1513, 2009.

[25] A. Nagase and N. Dunnett, "Drought tolerance in different vegetation types for extensive green roofs: Effects of watering and diversity," in Landscape and Urban Planning, 2010, vol. 97, no. 4, pp. 318–327.

[26] J. T. Lundholm, J. S. MacIvor, Z. Macdougall, and M. Ranalli, "Plant Species and Functional Group Combinations Affect Green Roof Ecosystem Functions," 2010.

[27] N. D. VanWoert, D. B. Rowe, J. A. Andresen, C. L. Rugh, and L. Xiao, "Watering Regime and Green Roof Substrate Design Affect Sedum Plant Growth," 2005.

[28] D. Wolf and J. T. Lundholm, "Water uptake in green roof microcosms: Effects of plant species and water availability," 2008.

[29] "Sedum spurium." [Online]. Available: https://plants.ces.ncsu.edu/plants/all/sedum-spurium/. [Accessed: 15-Jul-2017].

[30] K. L. Getter and D. B. Rowe, "Substrate Depth Influences Sedum Plant Community on a Green Roof," 2009.

[31] "Climate New York - New York," *U.S. Climate Data*, 2017. [Online]. [Accessed: 15-Jul-2017].

[32] P. Inc., "Statistics: Halifax, Nova Scotia - The Weather Network," *legacyweb.theweathernetwork.com*. [Online].

[33] US Department of Commerce, NOAA, National Weather Service, "Monthly & Annual Precipitation at Central Park," *National Weather Service*. [Online]. [Accessed: 15-Jul-2017].

[34] J. T. Lundholm, "Green Roofs and Facades: A Habitat Template Approach," *ResearchGate*. [Online].

[35] "Plants Database," *Welcome to the PLANTS Database | USDA PLANTS*. [Online]. [Accessed: 15-Jul-2017].

[36] M. A. Monterusso, D. B. Rowe, and C. L. Rugh, "Establishment and Persistence of Sedum," *HortScience*. [Online]. Available: http://hortsci.ashspublications.org/. [Accessed: 15-Jul-2017].

[37] "Vegetated Roof," *Friends Center*, 23-Jun-2016. [Online]. Available: http://www.friendscentercorp.org/?page_id=298. [Accessed: 19-Jul-2017].

[38] "Construction Worker Salary in New York," *Sokanu*. [Online]. Available: https://www.sokanu.com/careers/construction-worker/salary/New%20York/. [Accessed: 15-Jul-2017].

[39] "GSA Green Roof Benefits and Challenges," *GSA Home*, 23-Aug-2016. [Online]. Available: https://www.gsa.gov/. [Accessed: 15-Jul-2017].

[40] "Exit Stair Width," *Building Code Sketchbook*, 20-Mar-2014. [Online]. Available: http://buildingcodenyc.com/sketches/exit-stair-width/. [Accessed: 15-Jul-2017].

[41] "Gutters - Gutter Guards, Gutter Machines & Accessories | | Gutter Supply," *Gutters - Gutter Guards, Gutter Machines & Accessories | | Gutter Supply*. [Online]. Available: https://www.guttersupply.com/. [Accessed: 15-Jul-2017].

[42] "Roof Assemblies and Rooftop Structures," *PDF.js viewer*. [Online].

[43] "Scupper Drain," *Jay R. Smith*. [Online]. Available: https://www.jrsmith.com/scupper-drain. [Accessed: 19-Jul-2017].

[44] "1938 Building Code," *Buildings - 1938 Building Code*. [Online].

[45] "New York City Snowfall Totals & Accumulation Averages." *Current Results*. N.p., n.d. Web. 20 July 2017.

[46] Rettner, Rachael. "The Weight of the World: Researchers Weigh Human Population." *LiveScience*. Purch, 17 June 2012. Web. 20 July 2017.

[47] "Managing Energy Costs in Office Buildings," *Madison Gas and Electric - Madison, Wisconsin*. [Online]. Available: https://www.mge.com/. [Accessed: 15-Jul-2017].

[48] K. Liu and B. Baskaran, "Thermal performance of green roofs through field evaluation," 2003.