Climate-responsive evidence-based green-roof design decision support protocol for the U.S. climate

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ABSTRACT: A number of trends have recently emerged in the areas of environmental building designs and high-performance systems. However, in spite of many design and technical efforts to improve building performance by using multiple building enclosure components, especially green roofs, the uncertainty of existing mechanisms, such as pre-defined computational modeling and design guidelines, has frequently resulted in lower performance efficiency than intended by the design. In reality, examination of many actual green roof performance cases revealed an even larger energy usage and/or lower environmental performance of the buildings, where implemented, than those of the adopted base cases. To address this challenge, we established a methodology for Climate-Responsive Evidence-Based Green-Roof Design Decision Support Tool that uses finely tuned performance modeling with calibration by the actual measured data from existing best practices. By utilizing these composite best-practice cases as a source for reference data, this project would be able to provide stakeholders (e.g., architects, facility managers, building / roof engineers, owners, etc.) with readily applicable and reliable green roof design solutions for new / renovation projects. To develop a design solution algorithm, multiple computational data mining methods and performance simulation modeling will be adopted. This project approach can lead to effective green roof design decisions in an early stage of an individualized project in various climates and under different geometric conditions, based on integrated principles of design and building architectural configurations. This will ultimately lead to better Urban Heat Island (UHI) effect mitigation.

KEYWORDS: Calibration, Simulation, High performance system, Urban Heat Island.

INTRODUCTION

A green roof is any roof, which usually, consist of plants growing on them but they perform just like any other roof. The important role of a green roof like any other roof is to provide shelter from heat, cold, snow, rain and wind. A green roof is nothing but a convection roof which consists of soil and plant layers along with the waterproofing membrane. Green roofs as mentioned before depends on various parameters like the composition of a green roof, insulation, vegetation type (extensive or intensive). All these parameters vary and are influenced by the climate zone they are located. Designers, Contractors and Clients although understand the importance of a green roof, they don't have much needed knowledge regarding the variation in green roof construction with respect to the climate to benefit the maximum savings on energy in terms of energy. Having the right knowledge about the variations in the green roof construction based on climate zones they are located in can benefit in terms of energy saving and in turn making it more economic. This can overall increase the growth in the construction of green roofs across the globe. This research is going to be based on various parameters involved in the designing of a green roof to reduce the heating or cooling load on the building in multiple climatic conditions in the U.S. For the climate selection, I have chosen Los Angeles classified as hot and dry (DOE climate zone (CZ #3), Missouri which is humid (CZ #4). Since green roof depends on soil composition, plant type, climatic condition, etc. On-site measured data is going to be collected and simulated performance data. The study will show how the climate influences the composition of a green roof and then will arrive at a basic conclusion on what a green roof composition should consist of based on the climatic zone based on accurately calibrated performance models using the measured raw data. The research will include simulation model calibration to estimate energy and environmental performance of green roofs in a few climates of the U.S.

1.0 OBJECTIVES

Rise in energy cost of a building, gave rise to increase in green roofing system. Although green roof has many advantages, like reducing UHI, improving air quality, storm water runoff etc. My research aims at studying the impact of reducing the load of a building by green roofs in the chosen climate zone.

1) Effectively model green roof assemblies for a building, in an energy modeling program, and calibrate those models based upon the use of existing data collected from a selected reference site.
2) Identify the role of the different parameters of a green roof assembly and quantify their impact on a building's heating and cooling loads.
3) Determine if a green roof (as a roofing option for different climate types) is a better alternative for cooling a roof, in terms of the thermal performance of the building.
4) Estimate the environmental performance and water usage/ quality management based on the evaluated energy performance and design configurations.
5) Develop the research findings in the form of a web-based decision support tool that is accessible to the public.
6) Facilitate and undertake further tool development as a means of opening new avenues of meaningful research with respect to evidence-based high-performance design.

2.0 PROJECT METHOD

As a step towards the research goal and objectives of this proposal, the project design and methods will include four steps: 1) Roof modeling and calibration, 2) Roof parametric data analysis, 3) Thermal and environmental performance, and 4) Development of a design decision tool.

2.1. Roof modeling

Two climate zones from United States were chosen to study the green roofs with respect to climate. The chosen climate zones were climate zone 3, which is hot dry and climate zone 4, which is humid. Two places in the chosen two climate zones were selected, namely California and Missouri. Temperatures at different levels of green roofs in the selected climate zones were collected over a period of 4 to 15 days in both California and Missouri, using various sensors and the data as recorded.

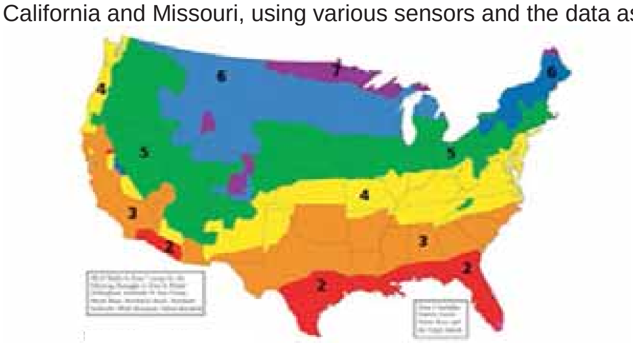


Figure 1: Represents the various climate zones.

2.2. Selecting the site to place sensors

Site in California:

The site chosen in California was, the Burbank Water and Power Building, located in Burbank. Burbank has a Mediterranean climate. The building was two story, constructed in 2012.It is LEED Platinum certified building.

Figure 2: Green roof on Burbank Water and Power Building (California).

Site in Missouri:

The site chosen in Missouri was, Emerson Electric Company Hall at the Missouri University of Science and Technology in Rolla, Missouri. The climate is humid subtropical, with 1227 mm average annual rainfall. As part of the roof renovation, a GAF Gardenscapes green roofing system with an area of 3,245 sq. ft was installed in the year 2013.

Figure 3: Green roof on Emerson Electric Company Hall (Missouri).

2.3. Checking for errors in the sensors

The sensors used in collecting the data in Burbank was the HOBO, It was important to check for the errors in the sensors before placing them to record data. Hence, all the HOBOs used for recording the data was placed together in a place, the data was recorded every 10 minutes over a period of 48 hours and then checked for errors. The graphs of the data showed uniform temperature and humidity reading. The maximum temperature difference between the sensors was .02 degree F, proving that the sensors could be used, since none of them showed no errors and the temperatures recorded by them were almost constant.

The sensors used in collecting data in Missouri were the Thermocouples, The thermocouples were prepared by exposing an inch of wire at one end, wrapping the two metals together, binding them with a blow torch, and then covering the probe tip with plastic dip paint. Due to the large scale of the project and varying locations of the probes, the lengths of thermocouple wire used vary from 25' to 235'. In total, around half a mile of thermocouple wire was used. The wide variety of lengths necessitated that the measurements be calibrated so as to eliminate any inconsistencies in the temperature readings resulting from the differences in wire lengths. To do this, the wires were left overnight while a data logger recorded temperature data at 3-second intervals. A graph of this data showed the thermocouples slowly approach a uniform temperature reading. Once this uniform reading was reached, the small differences among each thermocouple were taken as offset values (Stuart Baur, Investigating and Analyzing the Energy Performance of an Experimental Green Roof System Installed on an Institutional Facility 2013)

2.4. Placing of sensors and a data collection

Placing the sensors in Burbank, California

First, the green roof in the Burbank was divided into two parts the vegetative and the non-vegetative part. The non-vegetative part consisted of the glass decoration which were placed on the roof. The sensors were placed at various levels of both the vegetative and non-vegetative part of the green roofs. In the vegetative part of the roof the HOBOs were placed 2 feet above the green roof surface, to capture ambient air temperature on the surface of the green roof, beneath the soil at a depth of 4 inches and another HOBO was placed below the concrete surface from inside of the building has shown in the *figure* below . Another censor was placed at the working level inside the building. The HOBOs used on the surface of the soil and green roof were covered with aluminum papers to reduce the impact of solar radiations on the temperature reading. The HOBO under the soil was placed in a plastic bag, with holes for the air to pass.

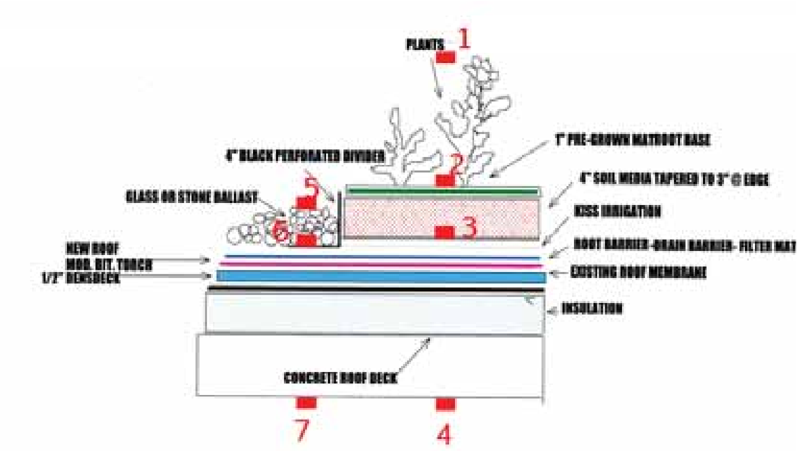


Figure 4: Section of the green roof showing all the placements of sensors.

Figure 5

Figure 6

Figure 5: The sensor placed to measure ambient temperature and humidity.
Figure 6: The sensors placed below the slab to measure the concrete temperature.

In the non-vegetative part of the green roof, HOBO was placed on top of the glass decorations which was again covered with aluminum paper for the same reasons as mentioned above, below the glass decorations again placed in a plastic bag with holes for the air to pass and to the concrete surface beneath the green roof area from inside of the building.

Figure 7: The sensor placed on the glass material wrapped in aluminum paper.

The sensors recorded the Temperature and Humidity over the next 15 days for every 30 minutes.

Placing the sensors in Rolla, Missouri

The experimental setup in Rolla consisted of three primary sources of data collection: The thermocouples for temperature measurement, a heat flux sensor, and a weather station. Two probes were placed at each levels of a green roof, 2' above the black roof, 4" beneath the green roof soil, and 2' above the green roof. One probe was placed at the remaining locations: the surface of the green roof, and on the underside of the concrete slab beneath, the green, roof sections (figure 4).

To capture the ambient air temperature 2' above each roof surface, three identical stands were built out of pressure treated 2x4 and weighed down with either sandbags or concrete blocks (figure 5). To isolate the thermocouples from wind and solar radiation, they were placed inside a double layer of plastic containers.

The inner layer protects the thermocouple from the wind whilst allowing some airflow through small openings. The larger outer layer is spray painted white to so as to reduce the impact of solar radiation on the temperature reading. (Stuart Baur, Investigating and Analyzing the Energy Performance of an Experimental Green Roof System Installed on an Institutional Facility 2013)

Figure 8: The sensors placed at different levels in the green roof.

For the temperature readings on the underside of the concrete roof slab, the thermocouple probes were placed directly on the concrete. A 6” square piece of one inch thick r-board was pressed up against the probe to isolate it from the temperature of the air space below. The blocks and probes are affixed to the concrete with high-strength adhesive tape (figure 8).The probes were placed at semi-central locations on all roof surfaces (figure 9). In the case of the green roof, a location was chosen where the vegetation cover was an average representation of the whole roof. Thermocouple wires from each location were run into a watertight box on the black section of the roof that held the data logging equipment. (Stuart Baur, Investigating and Analyzing the Energy Performance of an Experimental Green Roof System Installed on an Institutional Facility 2013)

Figure 9: Thermocouples affixed to the concrete sub-slab beneath each roof section.

3.0 SIMULATION MODEL

After the collection of data from the green roofs in Burbank and Rolla, the next step is model the green roof on a building with the obtained data from the sensors. Building envelope and the components (HVAC systems) are the two most important factors of a building energy simulation model.

3.1. Simulation engine and graphic user interface

Energy simulation software have what is known has graphic user interface (GUI) and a simulation engine. The GUI is used to input files for simulations and also to display the simulation results. There can be multiple GUI for one simulation engine. For this research, 3D graphical design modeling software called Design builder, with EnergyPlus has its simulation engine is used.

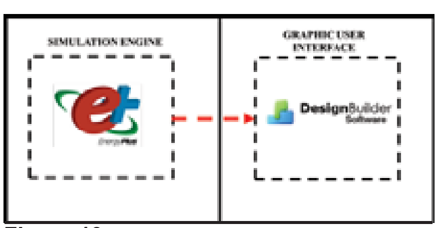


Figure 10: Energy simulation engine and the GUI.

3.2. Modeling a green roof in Design Builder with EnergyPlus engine

Lack of green roof design energy modeling tool, led Dr. David J. Sailor to develop a computational model of green roof which included heat transfer process in them. The green roof model designed by Sailor and his students at the University of Portland, was first used in Energy Plus v2.0. It was based on the FASST (***Fast*** All-Season Soil Strength) vegetation models for the US Army Corps of Engineers developed by Frankenstein and Koenig.

In Energy Plus the user can specify the eco roof as the outer layer for the roof construction options. The user must also specify other parameters involving the green roof construction which includes parameters like soil moisture conditions (including irrigation), plant height, growing media depth, plant canopy density, thermal properties and stomatal conductance (ability to transpire moisture).

The green roof model takes into account the following:

- Conduction of heat in the different layers of the soil.
- Evapotranspiration from the plants and soil.
- Convective heat transfer due to the plant canopy.
- Radiative exchange within the plant canopy, due to long and short wave of the sun.

3.3. Limitations of modeling a green in Design Builder

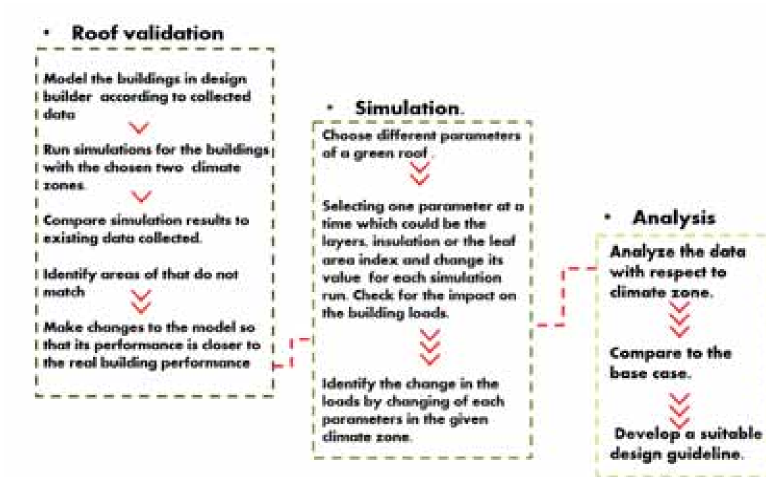
For the Conduction Transfer Function (CTF**)** algorithm to work, we need to input specific parameters with respect to the soil and plants. The parameters have specific ranges for the data inputs beyond which, we cannot input the data. The ranges for the various parameter are shown in Table 1.

Table 1: Ranges of various parameters input for Ecoroof model (The Encyclopedic Reference to EnergyPlus Input and Output 2011).

Parameter	Data range	Typical values
Height of plants	0.005m -1.0m	
Leaf Area Index (LAI)	0.001- 5	
Leaf Reflectivity	0.05- 0.5	0.18- 0.25
Leaf Emissivity	0.8 – 1.0	
Minimum Stomatal Resistance	50s/m – 300s/m	
Thickness (of layer)	0.05m – 0.7m	0.15m- 0.3m
Conductivity of Dry Soil	0.2W/(m-K) – 1.5W/(m-K)	0.3W/(m-K) - 0.5W/(m-K)
Density of Dry Soil	300 kg/m^3- 2000 kg/m^3	400 kg/m^3- 1000 kg/m^3
Specific Heat of Dry Soil	>0.0 J/(kg-K)	
Thermal Absorptance	0.0- 1.0	0.9- 0.98
Solar Absorptance	0.0- 1.0	0.6- 0.85
Visible Absorptance	0.5 – 1.0	
Saturation Volumetric Moisture Content of the Soil Layer	0.1- 0.5	
Residual Volumetric Moisture Content of the Soil Layer	0.01- 0.1	
Initial Volumetric Moisture Content of the Soil Layer	0.05- 0.5	

4.0 METHODOLOGY

The research methodology consists of various phases, each phase dependent on the other and followed in the order of green roof model Validation, Simulation and Analysis as shown in the flowchart below.



4.1. Green roof model validation

Since, the research focuses on green roof modeling, a DOE2 model of office building is considered. The roof of this building is modeled to be Eco-roof using the design builder software. The Eco roof is modeled accurately enough to match the real case scenario.

This is done by modeling the roof assemblies on the DOE2 model from the data obtained (as mentioned in chapter 3) from the buildings with green roof in both Burbank and Rolla. The simulations are run to determine the performance of the green roof with the respect to climate zones and construction type. The simulation results are then compared to the green roof data that was collected. Changes are made to the model until a benchmark of +/- 20% difference between the actual field data and simulated data is obtained.

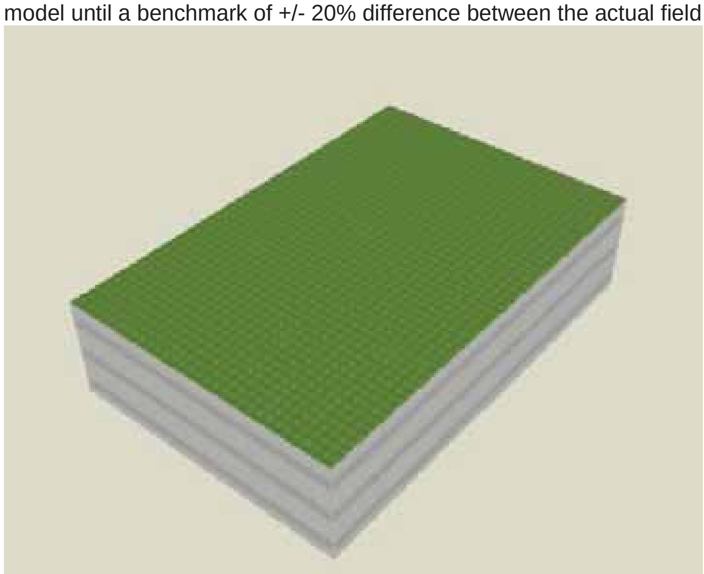


Figure 11: Green roof model for validation using Design Builder.

4.2. Simulation

Simulation phase is that phase in which, once the accuracy of the model against the field data is achieved the model is used for various parametric simulation study. The model is tested with various parameters in the chosen two climate zones. The main purpose of simulation running over various parameters is to study the impact of energy load of a green roof on the building with respect to the climate zones they are located in. Simulations also help us understand the thermal performance of the green roof with varying parameters involved the green roof.

There are various parameters on which the performance the green roof can depend on they are orientation, insulation, climate, height of the building , roof slope , soil depth , vegetation type , Irrigation, building function , drainage system , thickness of drainage system etc.

Figure 12: Various parameters that would be used in this research are shown in the section of green roof

In this research, four parameters that would be tested are Insulation, Soil Depth, Vegetation type and Climate type.

4.3. Parameter 1: Insulation

In any kind of a roof an insulation layer is optional, the same holds true even in the case of green roof. Green roof itself acts like an insulation, due to the soil layer and vegetation. Insulation boards in a green roof provide extra protection as they are placed under the water proofing member. The different subsets under the insulation that would be studied are:

- No Insulation.
- 4" Insulation.
- 6" Insulation.
- 8" Insulation.

4.4. Parameter 2: Soil depth

Soil depth in a green roof varies based on the type of the green roof being constructed. Based on the type of vegetation used for the green roof, they are classified into three categories of green roof with varying soil depth. They are Intensive, Extensive and Semi- Intensive green roof. For the construction of Intensive types of a green roof, the soil depth usually needs to be 12 inches or deeper. Green roofs with soil depth 2 inches to 6 inches, lie under the category of Extensive green roof type. Semi-Intensive green roof is one, where the soil depth lies between 6 inches to 12 inches.

The three sub parameters under soil depth that could be considered for this research are:

- 3" thick soil (extensive)
- 6" thick soil (semi-intensive)
- 12" thick soil (intensive)

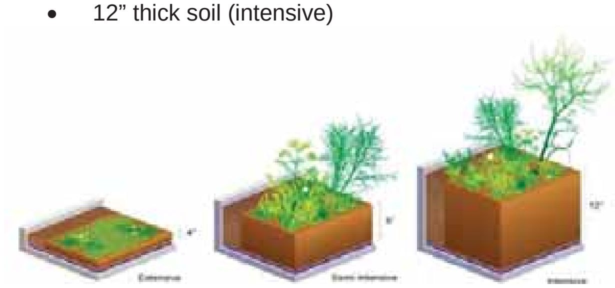


Figure 13: Different soil depths (Groundworks Sheffield)

4.5. Parameter 3: Vegetation type (based on the leaf area index)

Types of plants used on the green roof vary with geographical location. Not all plants can survive in varying climates of United States. Soil depth in the green roof, depends on the type of plants used. Plant type used on the green roof also has an effect on the thermal performance of the roof. Plants have different leaf area Index (LAI), LAI is defined as the amount of leaf area in a vegetation canopy per unit land area (Scurlock et al. 2001). LAI is one of the most important parameter in green roof, since it affects the heat flux between the plants and atmosphere. In other words, LAI provides solar shading on the roof surface.

The sub variables used are:

- LAI = 1
- LAI= 3
- LAI=5

Figure 14: Various LAI in plants.

4.6. Parameter 4: Climate type

Two climate zones are selected to study the thermal performance of the green roof with respect to various parameters. The climate zones chosen are:

- Climate zone 3 – Hot Dry – California – Burbank.
- Climate zone 4 – Humid – Missouri – Rolla.

CONCLUSION

On completion of all the simulation, the energy loads on the building are calculated and analyzed. The hypothesis which is **-** The impact of the efficiency of energy saving of a green roof depends on various composition parameters and the climate zone they are located in is tested. A part from that, the best combination of green roof parameters, with respect to the climate zone, to obtain a maximum thermal efficiency of the green roof is studied. Once this is completed, guidelines for designing the green roof to obtain the best thermal performance in the chosen two climate zones is developed, which could be possible by studying all the chart in details.

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