Climate-Responsive Evidence-Based Green-Roof Design Decision Support 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 the performance using multiple building enclosure components, especially green roofs, the critical uncertainty of existing mechanisms, such as pre-defined computational modeling and design guidelines, has frequently resulted in lower building 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 building, where implemented, than those of the adopted base cases. To address this challenge, we developed a Climate-Responsive Evidence-Based Green-Roof Design Decision Support Tool that uses finely tuned performance modeling with calibration by actual measured data from existing best practices. By utilizing these composite best-practice cases as a source for reference data, this project can 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. A design solution algorithm that was developed by this project adopted multiple computational data mining methods and performance simulation modeling. This project approach can lead to effective green roof design decisions in an early stage of an individualized project with various climate and geometric conditions, based on integrated principles of design and building architectural configurations.

1. INTRODUCTION

There is widespread recognition and a growing literature of measured data that suggest that green roofs can reduce building energy consumption along with providing environmental benefits [1–3]. Vegetated or green roofs can act as urban heat-island effect mitigation tools, where water evaporation from the vegetation, as well as the thermal mass and thermal resistance of the green roof, contribute to reduced indoor and outdoor temperatures in buildings and urban areas [4–6]. This, in turn, would help reduce the cooling load for a building, resulting in reduced cooling air requirements. Therefore, energy consumption would be reduced, as well as the associated output of atmospheric carbon [5,7] and the downsizing of the HVAC system for the building. However, the question arises as to whether the roof assembly is performing according to its design, and whether any alteration made to the assembly would make a difference in the building's thermal performance. In addition, the complexity of design configurations in design parameters (which should be considered in environmentally responsive design principles) demands considerable project effort and financial expenditures. As a result, most stakeholders routinely follow what they have done in previous projects, and /or adopt a "rule-of-thumb" experience that includes skipping the step that requires an in-depth climate-responsive design optimization process. Such an imperfect design process would probably result in much higher energy use and increased greenhouse-gas emission, while sacrificing effective environmental benefits in urban-heat-island effects [2,8].

Therefore, the goal of this project is *to provide a design decision support tool for green roofs, which would be useful in providing an environmentally-responsive parametric design with consideration of the climate and seasonal characteristics of a project site (Figure 1).* Thus, the developed tool will assist stakeholders in establishing optimized design solutions without sacrificing conventional design and construction processes.

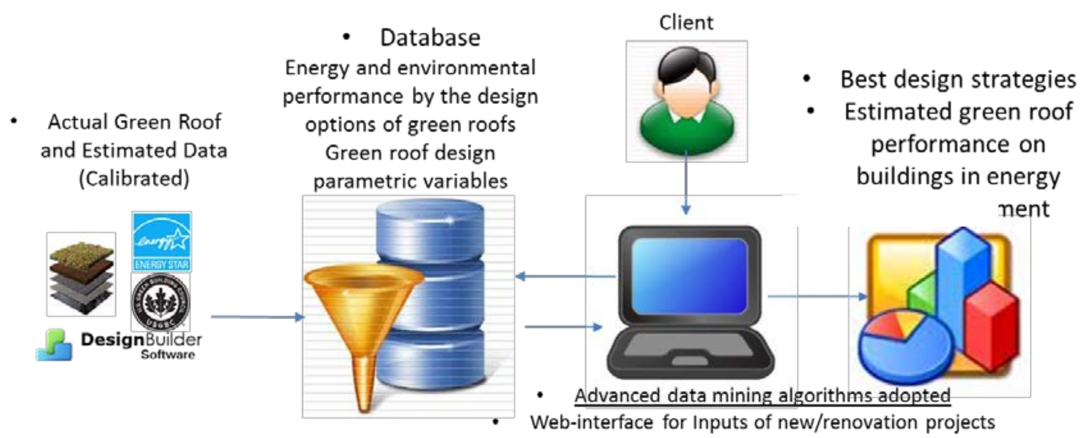


Figure 1. Conceptual diagram of the design tool process of this project.

2. OBJECTIVES

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 environmental performance based on evaluated energy performance and design configurations.
5) Develop research findings in the form of a web-based decision support tool that is accessible to the public.

3. PROJECT METHODS

3.1. Roof modeling and calibration

Objective 1: Effectively model a green roof assembly on a building, in an energy modeling program, and calibrate that model to match existing data.

Task procedure:

- Select an existing building with a green roof installed.
- Collect roof performance data pertinent to the selected building.
- Model the building with energy modeling software according to reference data collected.
- Run a simulation for the appropriate climate zone, and record the results.
- Compare simulation results to existing data, and identify areas of disagreement/ mismatch.
- Calibrate and fine-tune a model so that its performance is closer to that of the selected real green roof.

The research tasks associated with Objective 1 are critical since the collected data from existing facilities were used as reference data for the purpose of model calibration. Considering the variations in climate zones in the U.S., the project selected existing green roof building sites, located in three representative climate zones: Los Angeles, CA (Climate Zone #3), Rolla, MO (CZ #4), and Chicago, IL (CZ #5), as defined by IECC [9]. These selected climate zones have been validated as an ideal climatic condition for vegetation without concern about maintenance, precipitation, and temperature.

The site chosen for Climate Zone #3 was, the Burbank Water and Power Building, located in Burbank, CA (Figure 2). Burbank has a Mediterranean climate.

Figure 2. Green roof on Burbank Water and Power Building.

Figure 3. Green roof on Emerson Electric Company Hall.

The site chosen in Climate Zone #4 was Emerson Electric Company Hall at the Missouri University of Science and Technology in Rolla, Missouri (Figure 3). The climate is humid subtropical, with 1,227 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.For Climate Zone #5, we selected the City Hall of Chicago in Illinois (Figure 4). The climate is heat dominant, and the sky condition is clear or cloudy overall, with cloudy conditions in the winter season.

Figure 4. Green roof on the City Hall building of Chicago.

Figure 5 clearly shows different weather patterns at each selected climate site.

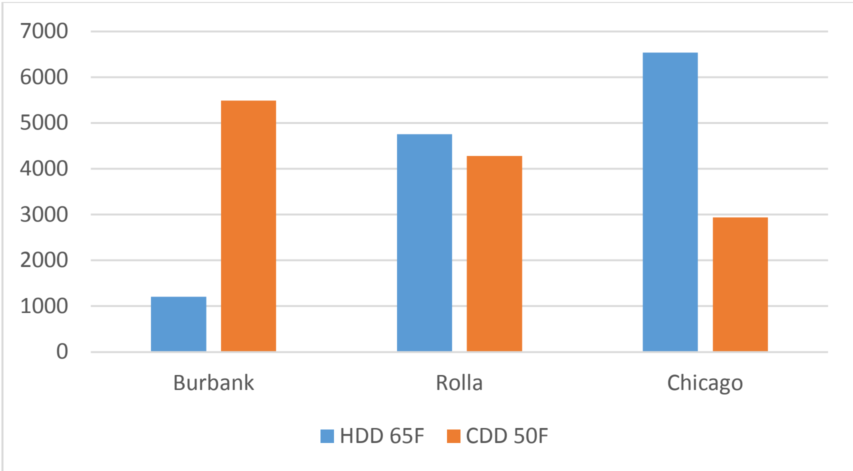
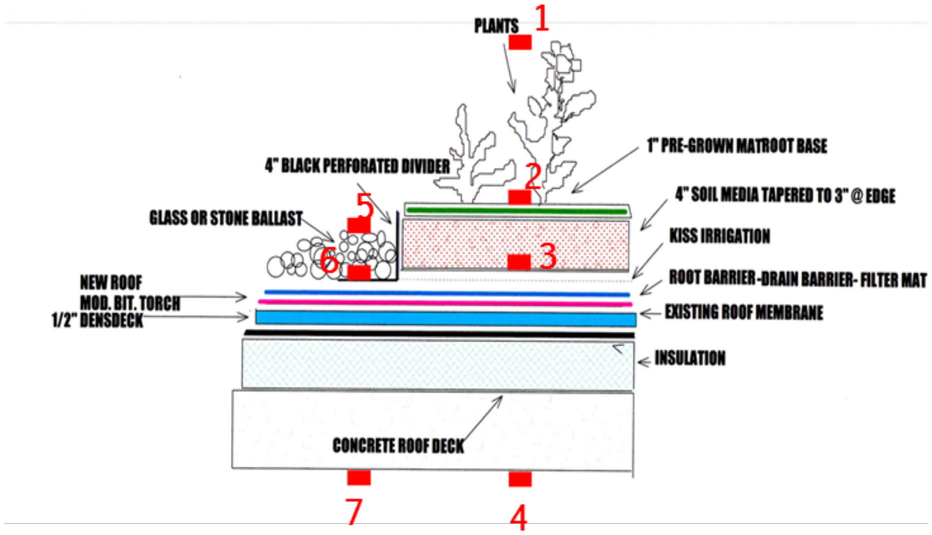


Figure 5. Heating and cooling degree days at each selected climate site (Y-axis unit: degree days).

3.1.1. Reference data collection

For reference data collection at the selected sites, the project adopted LM-35 (thermocouple) and HOBO sensory devices to measure dry bulb temperature and relative humidity. All of the data was recoded every 10 minutes. In the vegetated area, A sensor was placed under the soil at a depth of 4 inches and another sensor was placed below the concrete surface from inside the building, as shown in Figure 6.



HOBO 1 : Above the roof (Ambient Temperature)
HOBO 2 : On top surface of the roof
HOBO 3 : Inside the soil
HOBO 4 : Beneath the concrete surface roof
HOBO 5 : On top of the glass pebbles
HOBO 6 : Below the glass pebbles
HOBO 7 : Beneath the concrete surface
HOBO 8 : At the working level (Inside the building)

Figure 6. Section of the green roof showing the placement of sensors.

3.2. Roof Parametric Data Analysis

Objective 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.

Task procedure:

- Different layers of green roof assembly correctly/accurately modeled.
- Select one parameter (layer) and change its value for each simulation run, and record the impact on the building loads.
- Repeat the process for each parameter, and record the results.

We considered those structural parameters as input variables in the building simulation software. The major physical parameters included height, foliage area (leaf area), leaf reflectivity, leaf emissivity, soil moisture, soil depth, and insulation thickness (Figure 7). However, we selected leaf area index, soil depth, and insulation as design parameters to simulate the green roof performance of each selected site climate.

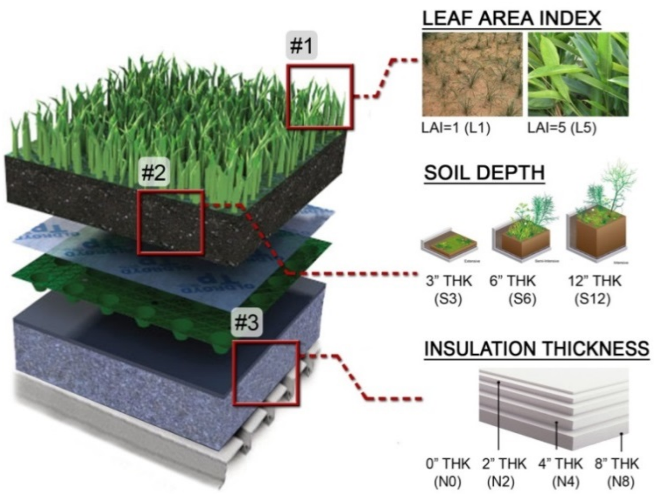


Figure 7. Test parameters and their subset variables.

3.2.1. Model Parameters Selected

We selected four major physical parameters in order to narrow down the parameters for parametric testing: Insulation, Soil Depth, Leaf Area Index, Insulation, and Climate type. These are currently adopted for modeling in the Energy Plus – Design Builder interface, based on the computation method designed by Dr. Sailor [10]. The variables selected in each parameter are as follows:

1) Insulation
   - No Insulation.
   - 4” Insulation.
   - 6” Insulation.
   - 8” Insulation.

2) Soil Depth
   - 3” thick soil (extensive)
   - 6” thick soil (semi-intensive)
   - 12” thick soil (intensive)

3) Leaf Area Index
   - LAI = 1
   - LAI = 3
   - LAI = 5

3.3. Thermal Performance Analysis

Objective 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.
Objective 4: Estimate environmental performance based on the evaluated energy performance and design configurations.

Task procedure:

- Replace green roofs with cool roofs in an energy model and run simulation.
- Compare the simulation results on the baseline model performance.
- Estimate the environmental performance and water usage/quality management as a function of the energy performance and design conditions.

Based on the optimized parametric combinations per climate zone, investigated in the previous tasks, we built a prototype building to evaluate the thermal performance of an optimally designed green roof. The building contains 53,600 sq ft (163.8 ft x 109.2 ft), five zones on each floor, and three stories (Figure 8). The code-compliance condition for ASHRAE 90-1 were applied per climate condition.

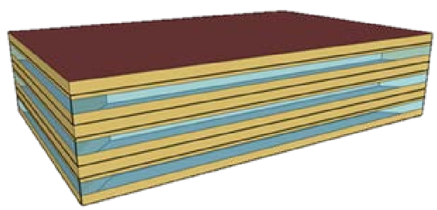


Figure 8. Isometric view of the baseline model adopted [11].

3.4. Development of a web-based design decision tool

Objective 5: Develop the research findings in the form of a web-based decision support tool that is accessible to the public.

Task procedure:

- Complete data interpretation and comparisons.
- Develop reliable computational models to estimate energy and environmental performance for each combination of selected parameters' configured variables of green roofs.
- Develop a web-based design decision tool that incorporates the estimation models and thermal performance data.

4. DATA COLLECTION AND ALAYSIS

4.1. Data Analysis and Interpretation

Once the baseline validation model was established to simulate each building performance with an acceptable accuracy, the green roof was reconfigured with various parametric combinations of the roof physical components selected. The simulation test was done for all of the 36 different assembly types in three different climates, with one variable of a parameter being changed with each simulation ran with the purpose of understanding how that variable affected the different thermal performance metrics that had been selected for this project. 36 parametric combinations can be generated based on the three parameters as follows (defined in 3.2.2.):

- L= Leaf Area Index (unit less) = 3 types
- S=Soil Depth (inches) = 3 types
- N=Insulation (inches) = 4 types

The nomenclature followed here is the same as described above and remains consistent throughout the report. For example, "B134" indicates an assembly with LAI=1, Soil Depth=3 inches, and Insulation=4inches. The other factors considered for simulation were the choice of one hot day and one cold day at each selected climate site.

4.1.1. Burbank, CA (Climate #3)

After simulating a green roof based on various parameters assemblies, the estimated cooling and heating energy loads in each design peak cooling and heating days, respectively, are summarized in Figure 9. The estimated energy loads vary depending on the design assembly.

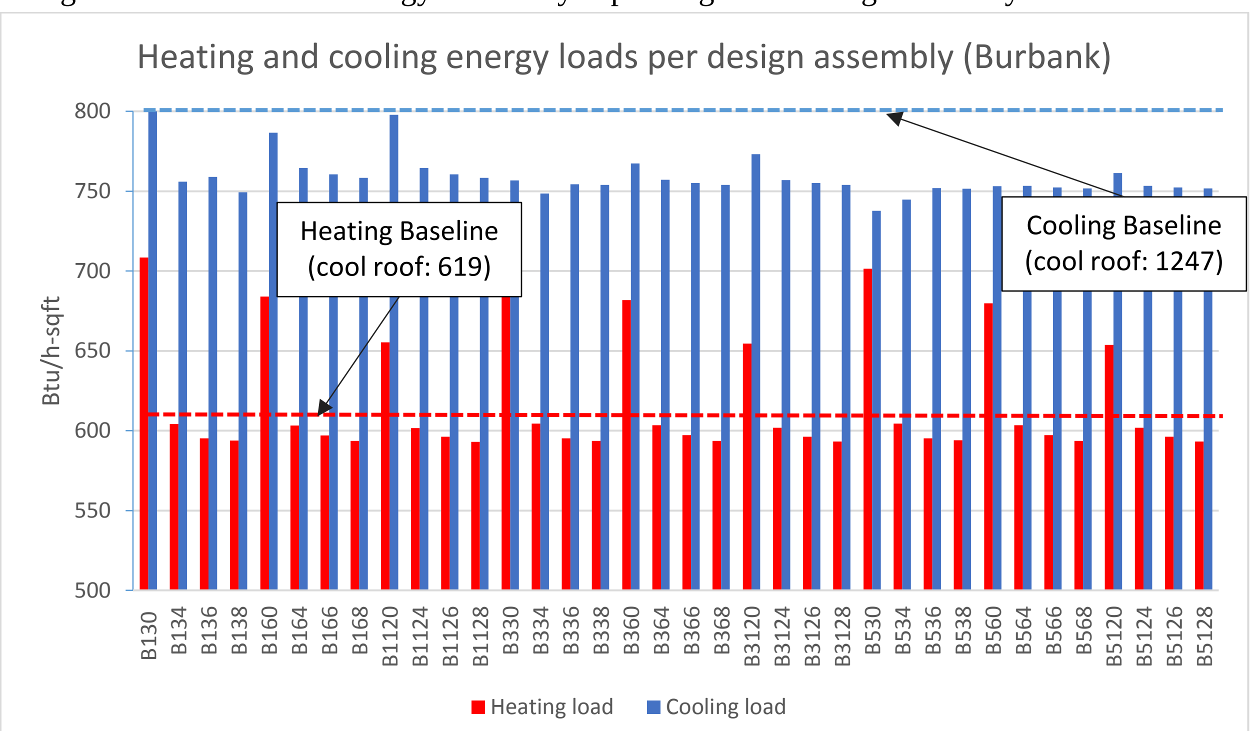


Figure 9. Heating and cooling energy loads per sq-ft (Burbank).

Per design peak cooling or heating day, a best 10 design assembly was generated, as in Figures 10 and 11. As illustrated in these two figures, a design assembly that generates the lowest heating energy load.

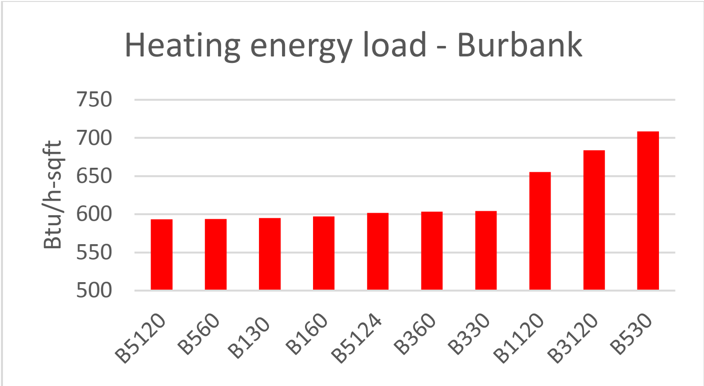


Figure 10. Heating energy load in Burbank.

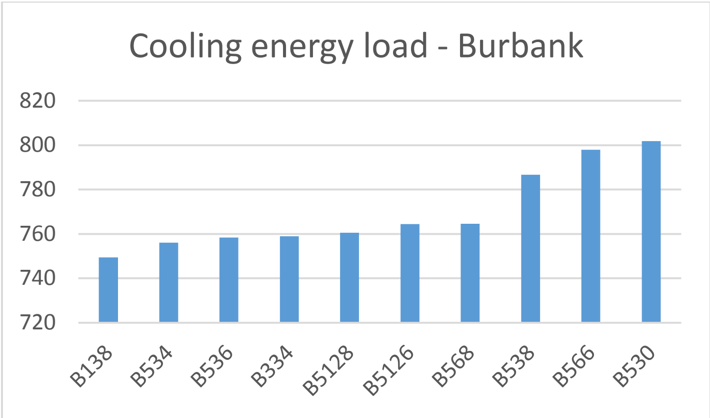


Figure 11. Cooling load in Burbank.

4.1.2. Rolla, MO (Climate Zone #4)

In Figure 12, like Burbank's results, the estimated energy loads vary, depending on the design assemblies. The design assembly with no insulation showed higher heating energy load than the baseline (which adopted cool roof), and the cooling energy load with no insulation also revealed higher values than the baseline in most cases in Rolla. However, Leaf Area Index with Insulation seemed to contribute to the cooling energy load reduction significantly. Among the parameters, Insulation was selected as the most significant attribute to building performance. LAI was estimated as a second significant parameter, while Soil Depth was counted as an insignificant attribute.

Per design cooling or heating day, a best 10 design assembly was generated in Figures 13 and 14. As illustrated in these two figures, a design assembly generating the lowest heating energy load, for example, does not guarantee its lowest cooling load, or vice versa. This was also similar to the finding in Burbank. Therefore, a duration of each season, i.e., cooling and heating seasons, should be considered to find an optimal design assembly which can minimize a total heating and cooling energy load in a whole year. This feature was discussed in Section 5, and the web-based design support tool incorporated a formula into the design algorithm, when could consider the duration of heating and cooling seasons.

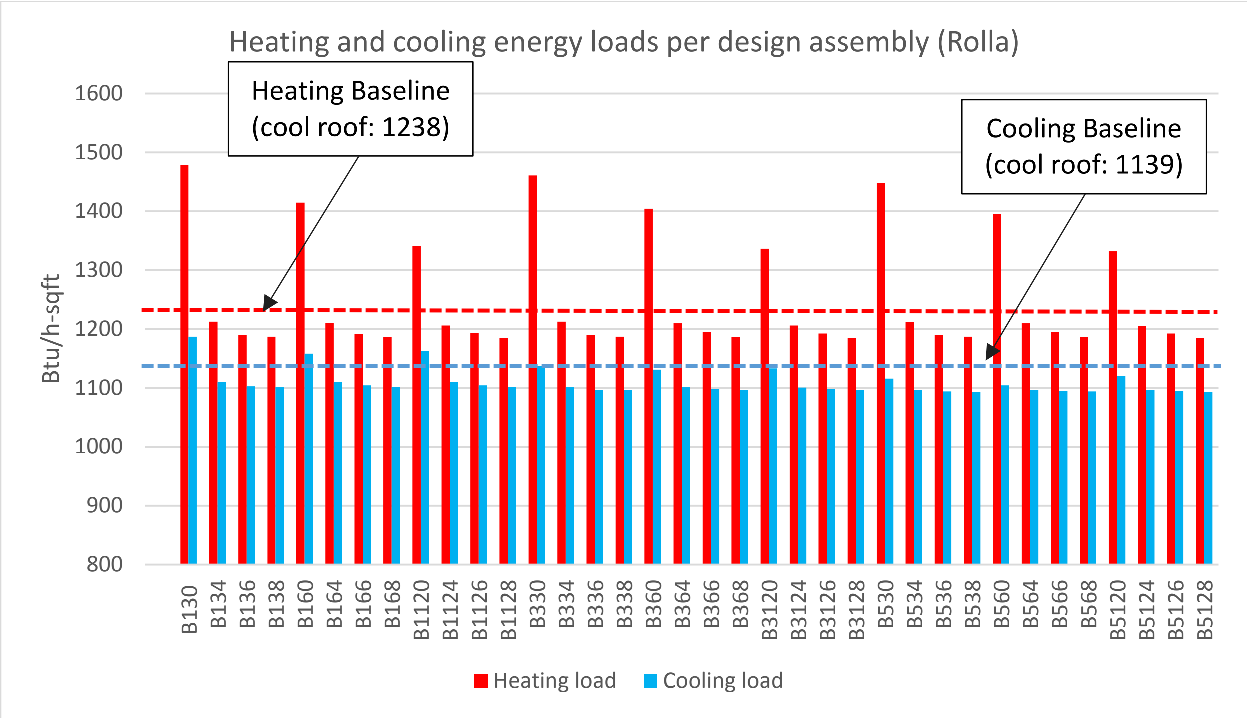


Figure 12. Heating and cooling energy loads per sq ft (Rolla).

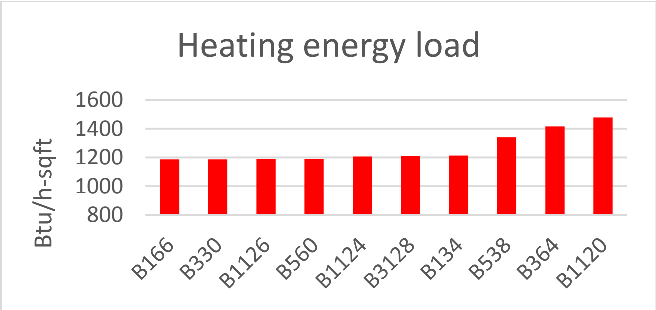


Figure 13. Heating energy load in Rolla.

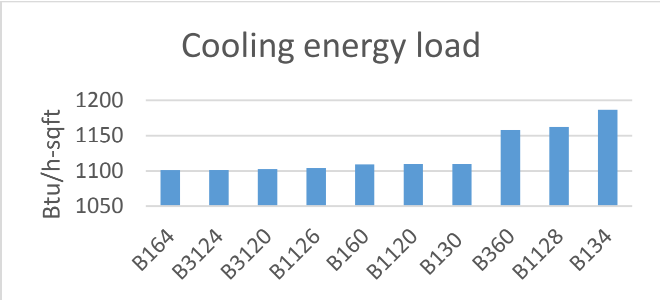


Figure 14. Cooling energy load in Rolla.

4.1.3. Chicago, IL (Climate Zone #5)

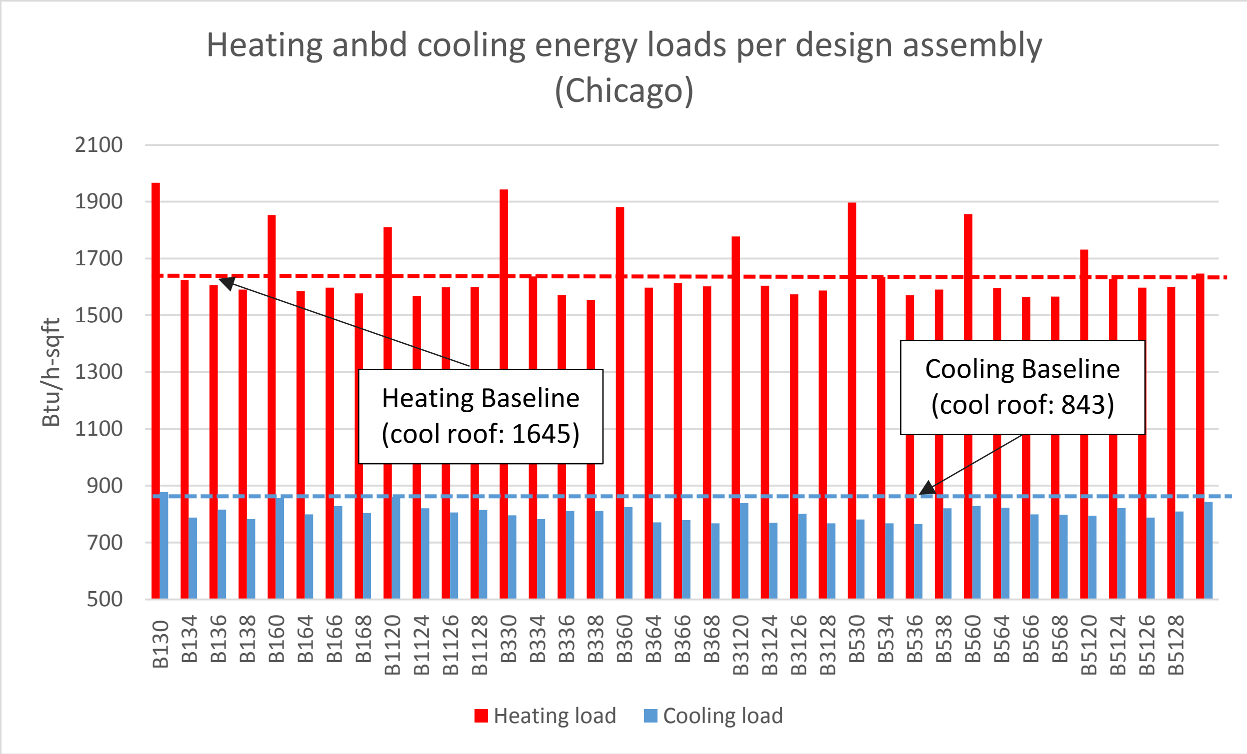


Figure 15. Heating and cooling energy loads per sq ft (Chicago).

Overall, the findings were very similar to those of Rolla. In the heating energy load analysis, LAI was not a significant component, as compared to Insulation and Soil Depth. However, in the cooling load analysis, all of the parameters were found to be significant variables.

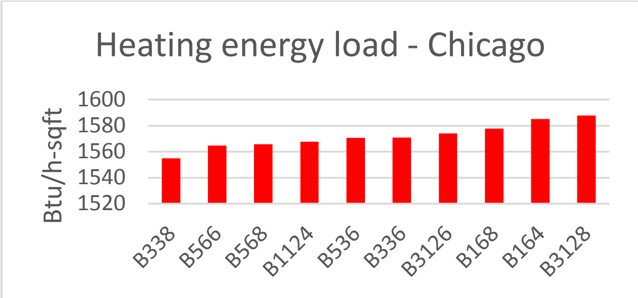


Figure 16. Total heating load in Chicago.

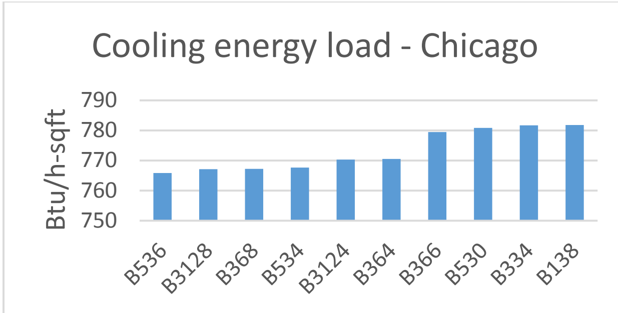


Figure 17. Total heating load in Chicago.

5. DESIGN DECISION SUPPORT TOOL

5.1. Design decision support model

Since this project considered three climate site conditions, the simulated data from the calibrated models totaled 216 data sets (216 = 36 design assembly x 3 cities x two conditioning seasons (i.e., cooling or heating)). In Section 4, LAI, Soil Depth, and Insulation contributed to the energy load/performance very differently, depending on climate conditions. In addition, a specific design assembly for one season did not guarantee its application to the other season as an optimal design solution. Therefore, the length of cooling or heating should be considered so that we can find an "optimal" design assembly to efficiently fit into the energy effective performance of a project for one whole year.

Since this project focused on finding an optimal design assembly of the green roof parameters, based on the use of simulation data generated by trustworthy simulation models, we put much weight on "differences" of the estimated energy performance by design. A climate condition is one of significant variables that affect green roof performance and help determine total building energy performance. Therefore, to establish a design decision algorithm, the project considered major climate condition attributes, which included heating and cooling degree days, 99% dry bulb temperature (DB99, for heating), 2% dry bulb temperature (DB2, for cooling), mean daily temperature range (MDR, for cooling), and 2% web bulb temperature (WB2, for cooling). This climate data information was taken from the ASHRAE Handbook-Fundamentals and ASHRAE Standard 90.1-2013 [12]. The formulas are as follows:

Table 1. Design decision support regression models.

Cooling energy load performance

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.964940	97.59%	97.47%	97.24%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value
Constant	32.74	3.63	9.01	**0.000**
LAI	-0.2549	0.0573	-4.45	**0.000**
SOIL DEPT	-0.0407	0.0250	-1.63	**0.106**
INSULATION	-0.2967	0.0318	-9.34	**0.000**
CDD 65	0.003816	0.000247	15.46	**0.000**
DB(2)	-0.2115	0.0312	-6.78	**0.000**

Regression Equation

Energy load (But/h/ft2)_1 = 32.74 - 0.2549 LAI - 0.0407 SOIL DEPT -0.2967 INSULATION + 0.003816 CDD 65 - 0.2115 DB(2)

Heating energy load performance

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.966891	97.74%	97.63%	97.41%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value
Constant	73.83	2.83	26.10	**0.000**
LAI	-0.2311	0.0570	-4.06	**0.000**
SOIL DEPT	-0.0339	0.0249	-1.36	**0.176**
INSULATION	-0.2845	0.0315	-9.05	**0.000**
HDD 65	-0.004988	0.000442	-11.28	**0.000**
DB (99)	-0.9792	0.0547	-17.92	**0.000**

Regression Equation

Eload (But/h/ft2)_1 = 73.83 - 0.2311 LAI - 0.0339 SOIL DEPT - 0.2845 INSULATION - 0.004988 HDD 65 - 0.9792 DB (99)

In Table 1, all of the selected variables were statistically significant with p-values lower than 0.10, except Soil Depth (p=0.17) in the heating energy load performance estimation.

Based on the estimated energy load per cooling and heating season, heating and cooling degree days were adopted in this project to estimate the length of each season and to calculate the total energy load for one year. These conditioning time lengths were multiplied to each estimated energy load per season, and the calculation results were used to select an optimal design assembly which could minimize the energy load for the whole year.

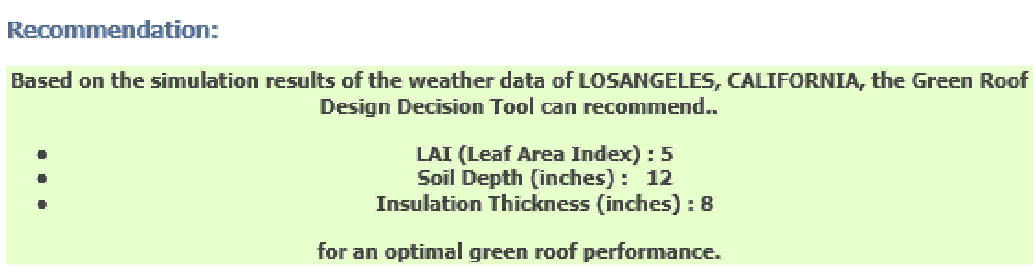
5.2. Web-based design decision tool

This tool is available in ***http://www.hbilife.com/rcif/*****.** This section introduces each page of the web-based tool and provides some instruction on how to use the tool and how to interpret the design decisions.

1) "Decision tool" page: a user can select a state and city of a project site by using a top-down menu. The embedded database contains data on 300 major cities in 52 states in the U.S. Once a project site is selected, a summary of weather data, including dry bulb temperature (2% and 99%), and web-bulb temperature (2%). Mean daily temperature range, as well as heating (60) and cooling degree (50) days are on the following page.

2) Result page: Based on the formula discussed in the previous section, the climate data of a site (selected by a user) and the green roof design assembly are processed to estimate the performance ranking of the assembly options for a cooling/ heating energy load, and the estimated EUI are displayed using the estimation engine embedded in the web-based tool.

3) Design recommendation: Based on the estimated total of EUIs for cooling and heating, the web-tool selects a design assembly which provides the lowest EUI estimation for recommending a best design solution for a whole year.



6. Conclusion and Project Limitations

6.1. Conclusion

The data-driven web-based decision support tool for a green roof design, developed in this project, provides a simple, quick, and easy, but evidence-based design solution-finding approach, using an advanced data mining logic. Building a simulation model is a challenge to building stakeholders, such as a constructor, manager, architect, or owner, mainly due to technical, time, and financial barriers. This developed tool adopts data-driven regression algorithms which are based on best practice data collected, calibrated simulated models, and computational data mining strategies in three different climate conditions. Since this design tool is already available to the public, it can be utilized for an early design decision-making on any type of green roof project.

6.2. Limitations

Limitations, with respect to this research, involve a lack of field data for validation in other climate zones. Although the United States is divided into six main climate zones, the scope of this research is limited to three climate zones only. Even though this project adopted 216 data sets generated from calibrated simulation models, the data size may not be large enough to generalize the findings and estimations for all U.S. site climate conditions. Therefore, the study of green roof performance in other climate zones would give us a much better understanding of the thermal performance of a green roof that pertains to a specific climate zone. In addition, this project adopted only four parameters, i.e., LAI, Soil Depth, Insulation, and Climate Condition. Various other parameters, such as Soil Moisture, Reflectance, Emissivity, and Absorption (apart from the chosen four parameters) could be selected and tested to identify robust findings and to incorporate them into the estimation algorithm.

Furthermore, future work could involve consideration of various other architectural parameters, such as types of the roofing system (sloped, flat, shaded, non-shaded, etc.), and different types of buildings, such as museums and hospitals, where an internal heat gain is not critical. Any or all of these could be investigated.

It would also be interesting to study the parameters that affect on-site air temperature and solar shading conditions that are mainly affected by neighbor buildings, especially in a high-rise business building district in an urban area. The air temperature and bounded solar radiation at a site could vary, depending on the construction of neighboring buildings. To study the impact of these on the site would be an interesting research topic which could help people in calibrating to validate a model in a super-fine resolution. In spite of the environmental benefits of green roofs, one of the main reasons not to choose a green roof as a top prior application may be the possible (technical) difficulty in physical management and the cost of maintenance. It would also be necessary to develop and study life-cycle and cost-benefit analyses of green roofs based on the design composition in each climate zone of the U.S.

7. REFERENCES

[1] H.F. Castleton, V. Stovin, S.B.M. Beck, J.B. Davison, Green roofs; building energy savings and the potential for retrofit, Energy Build. 42 (2010) 1582–1591. doi:10.1016/j.enbuild.2010.05.004.

[2] C. Clark, P. Adriaens, F.B. Talbot, Green Roof Valuation: A Probabilistic Economic Analysis of Environmental Benefits, Environ. Sci. Technol. 42 (2008) 2155–2161. doi:10.1021/es0706652.

[3] H. Akbari, M. Pomerantz, H. Taha, Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas, Sol. Energy. 70 (2001) 295–310. doi:10.1016/S0038-092X(00)00089-X.

[4] R. Kumar, S.C. Kaushik, Performance evaluation of green roof and shading for thermal protection of buildings, Build. Environ. 40 (2005) 1505–1511. doi:10.1016/j.buildenv.2004.11.015.

[5] E. Obernodorfer, J. Lundholm, B. Bass, R.R. Coffman, H. Doshi, Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services, Bioscience. 57 (2007) 823. doi:10.1641/B571005.

[6] M. Santamouris, C. Pavlou, P. Doukas, G. Mihalakakou, A. Synnefa, A. Hatzibiros, et al., Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece, Energy. 32 (2007) 1781–1788. doi:10.1016/j.energy.2006.11.011.

[7] K.L. Getter, D.B. Rowe, G.P. Robertson, B.M. Cregg, J.A. Andresen, Carbon Sequestration Potential of Extensive Green Roofs, Environ. Sci. Technol. 43 (2009) 7564–7570. doi:10.1021/es901539x.

[8] P. La Roche, Low Cost Green Roofs for Cooling, Csupomona.edu. (2009) 22–24. http://www.mendeley.com/research/low-cost-green-roofs-cooling/ (accessed September 11, 2014).

[9] IECC, 2012 International Energy Conservation Code®, (2012). http://shop.iccsafe.org/2012-international-energy-conservation-code-soft-cover.html (accessed September 12, 2015).

[10] D.J. Sailor, T.B. Elley, M. Gibson, Exploring the building energy impacts of green roof design decisions - a modeling study of buildings in four distinct climates, J. Build. Phys. 35 (2011) 372–391. doi:10.1177/1744259111420076.

[11] Department of Energy, HVAC Package for Small and Medium Sized Commercial Buildings, (2015). http://energy.gov/sites/prod/files/2015/05/f22/cbi71_Taylor_041515.pdf.

[12] ASHRAE, ANSI/ASHRAE/IES Standard 90.1-2013 -- Energy Standard for Buildings Except Low-Rise Residential Buildings, 2013. http://www.techstreet.com/ashrae/products/1865966?utm_source=promotion&utm_medium=landingpage&utm_campaign=86273&utm_term=86273&utm_content=86273&ashrae_auth_token= (accessed February 23, 2015).