Development and Validation of a U-BIM Model

For mitigation of the urban heat island effect

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ABSTRACT: Simulation programs can help predict the energy use of individual buildings, and the results can then be used to determine effective means of reducing consumption. It is also useful to look at collections of buildings, specifically the exterior surfaces of those buildings such as roofs and facades and interstitial surfaces, for example, parking lots, sidewalks, parks, and roads. This is especially important in urban areas, where density and hardscaping causes a condition called the Urban Heat Island Effect (UHI). This proposal summarizes the current and future development of an urban scale computer modelling software program that first combines solar insolation measurements, material characteristics, and vegetation to help designers to study, predict, and suggest solutions to mitigate the UHI effect and allow for testing of strategies such as albedo modifications and increased use of planted areas that may prove productive in lessening overall energy consumption.
Keywords: urban heat island, insolation, albedo, cool roof, green roof, energy simulation

INTRODUCTION

We all use energy in many forms in our day to day lives. Our understanding of its forms and conversions can be instrumental in determining how we conserve and harness it. The building sector is a major energy consumer. It is therefore imperative that we make the built environment energy efficient in order to achieve more sustainable design. While there has been a lot of analysis done at the building scale by architects and engineers, there is a growing need for analysis at the urban scale as well. We have to consider built form as a whole and use software to predict performance, suggest design changes, and help overall in making cities more energy efficient.

This objective of conducting analysis for energy flows can be achieved through digital simulation methods. Computer software and simulation packages are important tools for such analyses. They can inform the design and remediation of built form to enable energy conservation. The logical requirement therefore is to develop sophisticated energy modelling tools for mitigating some of the most pressing urban problems. This paper presents an in-progress research for the development of an extension to a software platform called Geospatial Decision Making (GeoDec) for urban heat island analysis.

URBAN HEAT ISLANDS

The issue of Urban Heat Islands (UHI) is of prime concern to architects and urban designers. Urban areas have a greater density of buildings and paved surfaces that absorb and retain heat from the sun. Typically overall, the relative air temperature is lower in rural areas, increases over suburban districts, and then peaks over urban areas. There are several reasons for this including the geometry of urban areas (canyons); choice of building materials especially ground and roof surfaces; additional heat from more buildings, people, and cars; and lack of vegetation.

As the sun rises in the morning, it is low in the sky and hits the east facing walls of buildings. In densely urbanized areas with tall buildings, the wall surface area that is exposed to this early morning warming is much greater than in rural areas that have fewer buildings. At noon, the sun's rays are perpendicular to and hit the horizontal surfaces below. These surfaces in urban areas include rooftops, roads, freeways, parking lots, and other hard paved surfaces that retain heat and warm up much more rapidly than soft surfaces such as parks and trees.

During the day, rural areas also get heated up. However, taking into account the additional early morning solar gain in urban areas, they are relatively cooler. This temperature differential causes air currents from urban areas to rural areas until about the evening time when the temperatures begin to balance out and surfaces start re-radiating heat back to the atmosphere in order to cool down. Again, due to the low evening sun and the corresponding solar gain on walls in urban areas, the temperatures in urban areas do not go down as rapidly as they do in rural areas, which get cooled by unrestricted surface winds. Thus the cycle of air currents from urban to rural areas repeats itself.

At night, since more of the surfaces in rural areas are able to see the sky (called higher sky view factor), they cool down faster. In urban areas, ground surfaces between tall buildings are not able to "see" the sky as much (lower sky view factor) and do not get enough cooling surface winds. The rooftops of buildings that are closer to the sky cool down faster and before the roads and pavements below. This causes temperature stratification in the air, further inhibiting heat loss of the ground surfaces to the atmosphere above. Therefore by morning, urban areas do not lose all their stored heat from the previous day to the environment but start getting solar gain for the next day. This makes urban areas hotter than rural areas already - before even beginning the new day's cycle.

As the day progresses however, the heat, dust and smoke from vehicles, mechanical systems, and other city processes adds particles to the atmosphere. This process repeated over time during the day leads to the formation of dome-shaped zones above urban areas that are hotter than the atmosphere around them. These are identifiable from the rural surroundings and form what are called heat islands in the larger landscape. The increased temperature in these zones does not allow dust particles to disperse in the atmosphere in the absence of rain or strong winds. These particles become heavier due to the deposition of fog on them and move downwards, fusing with other particles on the way. This increases the level of ozone formation near the ground and promotes the build-up of smog. [1]

During winter, the increased temperatures are beneficial as there is less heating load and the excess heat prolongs the growing season for plants. [2] However, during summers, the demand for electricity to cool buildings is much higher and this forces increased production of electricity – adding to pollution and fossil fuel usage. Thus summer losses far outweigh winter gains. In some urban areas, such as Los Angeles, office buildings can have cooling loads all year, including winter.

In summary, higher temperatures increase the need for cooling. Buildings thus consume more electricity. This also leads to increased pressure on the electrical grids to meet the greater demand – leading to environmental pollution from the production plants and the need to serve a higher peak demand. In addition, there are health concerns, such as respiratory problems, related to the build-up of smog and increased air pollution, and heat related illnesses and deaths. Separately, but related, with an increasing amount of hardscaped areas in the cities, there are fewer softscaped areas that allow rainwater to percolate into the ground. This causes a significant drop in the water table of the area, depriving residents of clean drinking water. This also hinders the capability of the ground surfaces to cool their surroundings and themselves through evaporation of surface water. Increased storm water runoff from paved surfaces washes the oil from automobiles, dirt on the streets and the like through pipes to nearby water bodies – contributing to their pollution. This affects the aquatic ecosystem of these water bodies. It is therefore important to analyze urban areas for heat build-up and take proactive steps to design a better built environment. Simulation of the micro-climate will aid in predicting the effect on heat island formation in urban areas.

UNDERSTANDING HEAT ISLANDS

There are many factors that we must know to make a first step in analyzing the problem and understanding the features that must be present for a simulation program to be useful.

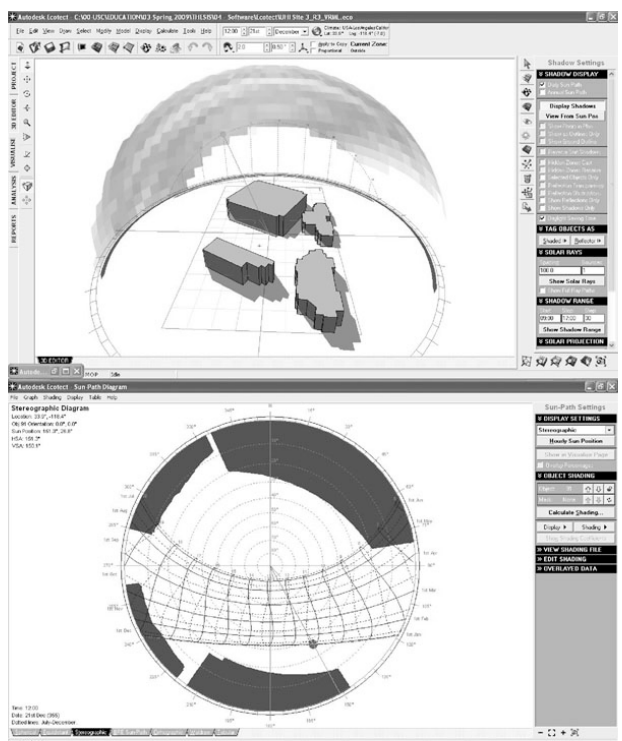

Figure 1: Insolation and sky map analysis using Ecotect [3]

The first is determining the incident solar radiation (**insolation**). The amount of solar insolation available in an area depends upon the geographic location of the building and the amount of solar radiation available at that time of the day and year. Theoretical available insolation can be derived from first principles, quarried from data available on solar radiation sky maps generated by government, or even pulled from TMY data available for thousands of locations collected over many years. The local insolation also heavily depends on the exact site being studied (Fig.1). There may be existing buildings, large signs, monuments, and other obstructions surrounding a building site that will affect the amount of incident solar radiation that directly hits the site at different times of the day and year. The site may be partially or fully shaded by these external elements. These variables are influenced by the prevalent weather – sunny, rainy, partly cloudy, etc. Therefore, one should be able to visualize the project in a larger model of the neighbouring urban environment for analysis.

Insolation and site geometry determine the available solar radiation. The materials of the buildings, paving, obstructions, etc. influence how it is used. For example, if a roof is dark in colour, it absorbs much more heat than if it is light in colour. Therefore, it is important to consider the **Solar Reflectance Index (SRI)** of the surface (e.g. building roof or sidewalk), which can be calculated from the reflectance and emittance for that surface. For new buildings, an architect has control over the selection of materials that have the highest albedo and emittance values to be used for successfully reflecting sunlight. But for existing buildings, it is important to determine the albedo of the surface under investigation. It may not be possible to test each and every surface that already exists in the surrounding built environment physically. One has to usually rely on approximation techniques for such situations.

For the purposes of this study, the author calculated the SRI of different surface materials in order to eventually determine their effect on heating up the external environment. Field measurements were taken on a site on the USC campus. Although far from being ideal, this location had some advantages – mainly convenience, that led to it being chosen. Field measurements were taken with a digital infrared camera; digital environment meter that measures air temperature, relative humidity, and illuminance; luminance meter; light meter; and infrared temperature gun. Not all of the measurements turned out to be useful. Several types of surfaces were included in the field measurements: asphalt, concrete, brick tile paving, metal, grass and shrubs, trees and other vegetation, soil in different conditions, pea and gravel surfaces, surfaces with a cool roof coating, and surfaces with tar and gravel coating. An example of infrared comparison of the surfaces with the actual photograph is presented in Fig. 2. Though difficult to see in the black and white representation of an infrared image, the light coloured pea and gravel roof is at approx. 46-56 °F as compared to the dark coloured brick tile façade that is at approx. 90-107 °F. Such data is helpful in determining the response of different roofing and paving materials to the solar insolation hitting them even on an overcast day.

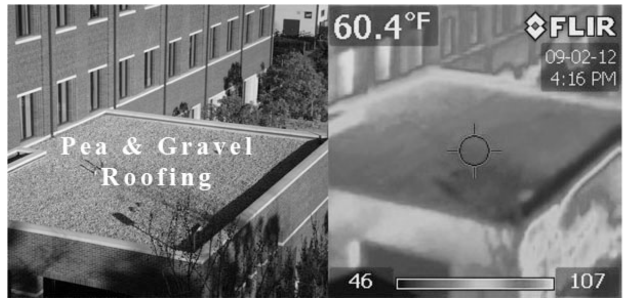

Figure 2: An actual-to-infrared photographic comparison of temperatures on a pea and gravel roof surface

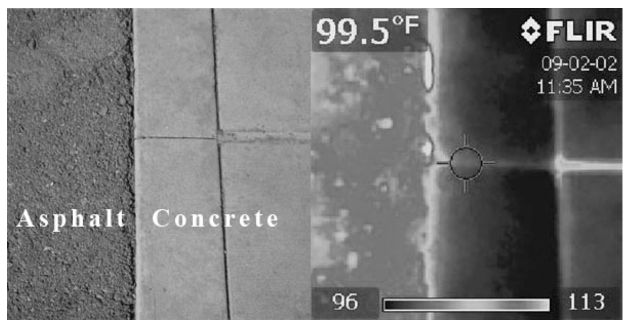

Figure 3: An actual-to-infrared photographic comparison of temperatures on parking lot pavement types

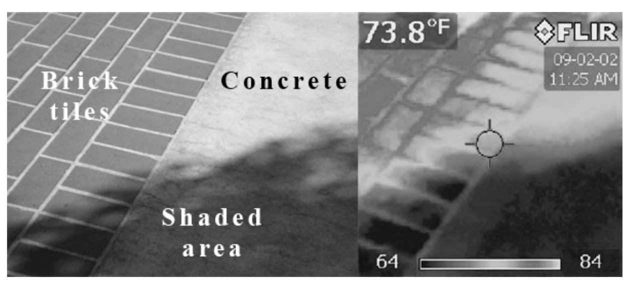

Figure 4: An actual-to-infrared photographic comparison of temperatures on different pavement types

The heating up of paved surfaces depends on their material properties as well as their shading from on-site elements. For example, in Fig. 3 we see that for the same unshaded outside conditions, the temperature of the asphalt pavement (approx. 108 °F) is much higher than the adjacent concrete pavement (approx. 96 °F). However, in Fig. 4 we can see how shading makes a difference to surface temperatures. Under unshaded conditions, the brick tile pavement is at approx. 80-84 °F as compared to the concrete pavement which is at approx. 74 °F. However under shade, the temperature drops to about 64-67 °F for both surfaces.

The illuminance measurements were done in two parts: one measurement was for the sky illuminance and the other was for the illuminance measurement taken parallel to the surface under investigation. The luminance was similarly measured in two parts: one for the surface under investigation and the other for a reference surface with a known reflectance. The **reflectance** of the test surface was obtained by the equation:

[Luminance of known surface/Luminance of test surface] = [Reflectance of known surface/Reflectance of test surface].

The **emittance** values of the surface materials were referenced from standard tables. The data depicts how reflectance and emittance values can be measured on site. These can now be used to calculate the Solar Reflective Index (SRI) for the surface materials. The ASTM E 1980 standard (Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces) was used to calculate the SRI from those two values. An Excel spreadsheet developed by Akbari [4] for this purpose was used. An alternate method of calculation is through the LEED® NC v.2.2 templates [5] for the Sustainable Sites credits 7.1 and 7.2 for heat island analysis that have the calculations built into them.

Another important site consideration is **vegetation.** While simulating the benefits of vegetation on the temperature of the surface under question (e.g. pavements or building facades), in addition to its SRI, it becomes important to factor in the effect of shade and cooling provided by vegetation around it. This component has a greater dimension to it as vegetation is temporally dynamic, for example, leaves may grow and disperse seasonally, and a tree may grow substantially over time.

However, there are marked differences in the surface temperatures of vegetated surfaces as compared to paved surfaces. This is one of the reasons why trees and vegetation are desirable in an urban environment full of paved surfaces. Consider a patch of grass exposed to direct sunlight in Fig. 5. We find that its temperature is between 43-58 °F. Compare this to the temperatures of paved surfaces that we saw in Fig. 3, which range from 96-113 °F. Both measurements were taken at the same date and time and at adjoining locations. Combining shade and vegetation is also an effective strategy for reducing surface temperatures. Consider a patch of grass shaded by a tree in Fig. 6, which is at approx. 50-55 °F as compared to the brick tile paving in the background, which is at approx. 80-82 °F.

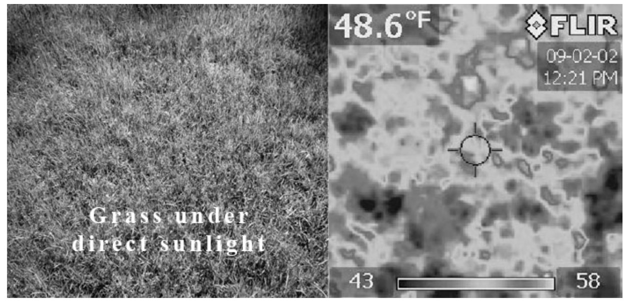

Figure 5: An actual-to-infrared photographic comparison of temperatures on a patch of grass under direct sunlight

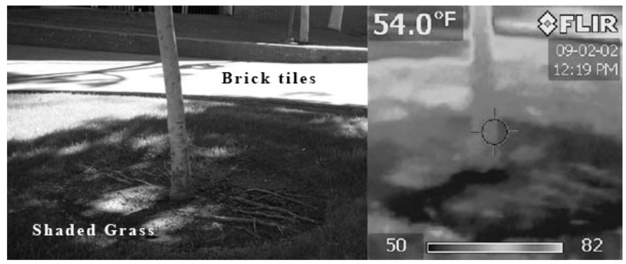

Figure 6: An actual-to-infrared photographic comparison of temperatures on a patch of grass shaded by a tree

The type and species of plants is important as different varieties have varying characteristics. Therefore, it is necessary to record the exact type of vegetation in the area of inquiry. In addition to the SRI of a planted area and the shading potential of the vegetation on neighbouring areas, evapotranspiration also plays a role in cooling the environment [6, 7]. This is however, outside the scope of this study.

DEVELOPMENT OF A HEAT ISLAND EXTENSION TO GEODEC

Computer software tools currently available to us allow better understanding of how a building will function once built. Parametric analysis can be used by designers to help determine better solutions before a building is constructed or suggest alternatives for remodelling in existing conditions.

GeoDec was chosen as the software program for this project. Geospatial Decision Making (GeoDec) [8] is a software platform that uses advancements in the fields of Geographic Information Systems (GIS), Global Positioning Systems (GPS), and satellite imagery to present elements and objects including buildings. GeoDec is a strong graphics engine and can be expanded for multiple functionalities (Fig. 7). However, new features for simulation and design analysis needed to be added to make it useful for heat island analysis. As development continues, these capabilities will be validated by other software programs.

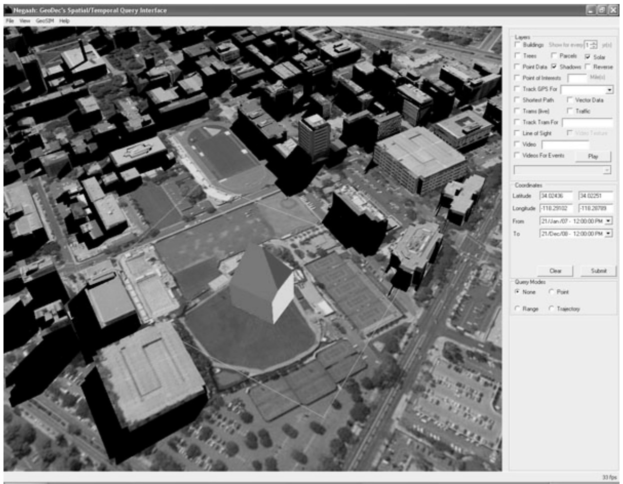

Figure 7: Recent additions to GeoDec include shadow casting and solar envelope generation capabilities (see foreground)

The current scheme for developing the extension of GeoDec includes the elements discussed under “Understanding Heat Islands” and has the following intermediate steps:

- Build site geometry. GeoDec will import a VRML file into an exact geographic location of the site in a photorealistic environment. It does not yet import other common formats. Although the program has other features not applicable to this project, from this point on, the authors have been working together with the programmers to increase functionality.
- Determine location. Calculate solar position. Cast shadows. This has already been accomplished, but does not take into account the relative “blackness” of shadows due to the available ambient light.
- Create solar envelopes. The program will do this for certain dates and times. This is only tangentially related to this project, but is important for urban solar policy and to aide design for daylighting and to determine the locations for placement of solar photovoltaic panels.
- Create inverse solar envelopes. Almost done. The program first calculates a daily and yearly shadow volume associated with the buildings. This is then used to create a volume on a specific site that is not currently shadowed by its neighbours. Once again, tangential to the study, but useful for designers.

The following are the upcoming steps:

- Incorporate the idea of a “building.” For example, all horizontal and vertical surfaces for a building are to lie on a single zone or layer (holding discrete editable values for each surface at the same time), making it possible to select the whole building as a single entity for analysis in an urban environment.
- Program the ability to attach attributes such as material data to the surfaces in the model.
- Create a library of materials in GeoDec and store their reflectance and emittance values in a database with them. When a user selects a material, the corresponding reflectance and emittance values should get applied to the model.
- Calculate insolation values either from first principles, simplified calculations, sky map data, or TMY weather data (solar availability direct, diffuse, and total insolation).
- Add visualization tools for temporal viewing. To visualize the reflectance and emittance values, GeoDec could break down each surface into a grid or create an overlay that can be divided into a grid. This grid will visually and numerically display insolation, surface temperature, and other similar characteristics such as SRI and albedo as well.
- GeoDec should be able to import and then help users visualize other TMY weather data including wind (direction and speed) and rainfall and humidity data.

At this point, the designer should be able to make rough comparisons between possible solutions. GeoDec can be made a more sophisticated heat model by adding other extensions to it, including:

- Analyze time lag due to differences in thermal mass. For example, for a selected time period, the insolation available at that location will hit the model surfaces – some will be reflected and a part of the heat energy will be absorbed. This will get emitted after a time lag according to the emittance properties of the surfaces. In addition, this emitted heat during the specified time period will affect the external environment. From this one can graph the rate of heating and calculate the total heat contribution of the model surface.
- Include calculations for energy losses from buildings based on their usage and associated internal loads. For this, one might use satellite thermal imaging data being independently studied for heat island analysis into the GeoDec model or acquire this information from the building information model for the project, if available.

Although vegetation is crucial to this study, it has not yet been incorporated into the study except with regard to the calculation of solar reflection indices. Here is a rough idea of what might be necessary to incorporate calculations for determining the cooling effects due to vegetation into GeoDec:

- Create a library of trees and other forms of vegetation. This would have to include at least the following information:

- suitability for a given area (for example, list native plants for a given area)
- shape and transparency (leaf area index) seasonally; rate of growth
- water requirements
- evapotranspiration rate (this is a complex calculation that includes many variables including plant type, rainfall, relative humidity, dew point temperature, watering requirements, etc.)

As a side note, since GeoDec can be simultaneously adapted for multiple visualization and analysis functions, one of the applications that utilize the information above is the study of building generated glare.

The combined effect of the different considerations identified above allows us to get an accurate picture of the conditions on site due to an existing or proposed design of the built form, experiment with the different options, and achieve an acceptable result that would increase the life of the building, lower the energy consumption, and contribute to reducing the heat island. For example, if a large building's roof is partially shaded by surrounding buildings and there is still a large area that is exposed to the sun, one can use a mix of strategies including selecting beneficial locations for the installation of solar photovoltaic panels, wind turbines, green roofs, cool roofs, after leaving area required for building services, amenities and usable rooftop area for occupants' use.

CONCLUSIONS

GeoDec is not nearly complete with regard to these extensions. But when finished, it is hoped that designers can benefit from heat island analysis for surfaces such as building rooftops, façades, pavements, driveways, parking lots, etc. Such analysis can also help them to:

- Test insolation and SRI effects on different surfaces in their design and look for options to reduce heat gain.
- Test and select appropriate glazing type for handling the incoming solar radiation on a particular façade.
- Design shading devices.
- Determine the placement of solar photovoltaic panels.
- Select vegetation for planting adjacent to built areas.
- Select appropriate cool/green roofing areas. For example, if the roof of a building is totally shaded by neighbouring buildings, the owner can protect his building by a relatively low cost measure such as a cool roof. If however the roof is gaining a high amount of solar radiation, the owner can invest in strategies such as a green roof to reduce internal heat gain and increase the life of the structure.
- For horizontal surfaces such as roads and pavements, heat island analysis will help city managers to take specific measures for improving them. Big parking lots that are usually covered with asphalt have a large amount of heat gain. Such surfaces also do not let any rainwater to permeate through them - leading to increased temperatures and surface runoffs. Heat island analysis can help parking lot owners to identify problem areas and resurface them with perforated concrete grid pavers or similar materials during the next scheduled maintenance. Such measures introduce pleasing softscape in the community and lower air temperatures, while promoting rainwater percolation to the ground.

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