Microclimatic Design
of Rooftop Gardens and Urban Courtyards

Abstract

Computer models were developed to predict the effects of design on microclimates in the roof garden and urban courtyard of the proposed New York Times Tower in Manhattan. A three-dimensional computer model of the building and its urban environment was integrated with a solar simulator to identify solar radiation zones within the spaces. This information, along with the results of a wind tunnel simulation, was used to recommend species of trees for the spaces. The solar simulator was also used to generate hourly solar and terrestrial radiation data for typical spring, summer, and fall days. These results, along with hourly air temperature, wind, and air humidity estimates were input to a human thermal comfort model. The resultant comfort levels across the garden were mapped and used to assist the design of the spaces. The interactive ability of the model allowed for design modifications to be tested for their thermal comfort effect. After construction the resulting urban spaces will be evaluated through measurement of microclimate variables and human use.

Introduction

As the cost of urban properties escalate, developers are rethinking the use of ‘remnant’ rooftop spaces which were traditionally relegated to mechanical systems. The rooftop affords some of the best views and the ‘penthouse’ has long been considered as the most prominent private space in most buildings. Greening these rooftop areas provides many benefits to the users, the developer and other city residents. More and more developers are recognizing the marketability of public rooftop gardens and urban courtyards in new developments.

There is mounting evidence that simply viewing natural landscapes can have a positive effect on the health and well-being of people. This finding has the potential to impact both the user of the rooftop gardens and other high rise workers or residents looking down on adjacent rooftops.

Rooftop gardens are not a new phenomenon in urban construction. Their cost and short window of use have been viewed as the main drawback to more widespread adoption. Recent developments are proving that, if effectively designed, the benefits of these spaces can far outweigh the costs and as a result, contemporary design approaches have placed a much greater emphasis on making these spaces comfortable for people and habitable for plants. New modeling and simulation technologies provide a means to assess the comfort and survivability (for plants)of these spaces. Microclimatic design of these spaces is now becoming a prime consideration in the planning and design process.

The thermal comfort of people in outdoor urban environments is often adversely affected by high winds in fall, winter, and spring, and by large amounts of solar radiation in summer. It is important to design urban outdoor spaces so that people will be comfortable using them for as much of the year as possible. Similarly, the selection of the most appropriate plants for these spaces requires a detailed understanding of the environmental conditions including light/shade, wind sheer, freeze/thaw, etc. Plants, in turn, can modify the microclimate of these spaces making them more or less hospitable for people.

This paper describes the process used to assess the microclimatic conditions for the proposed 53 storey New York Times Tower in Manhattan, New York. The study used a series of computer models to help recommend trees that could grow in various microclimates across a site. The COMFA model (Brown, 1995) was used to determine the thermal comfort level of people using the different environments in the site. The results of both models were used by the project landscape architects to design the most suitable spaces.

Models:

1.0 Tree Selection

The component models for the tree species recommendation (TSR) system included a solar simulation and wind prediction model who's results were cross referenced with a plant database.

For rooftop garden and urban courtyard design, the selection of *annuals* and *perennials* is primarily dependant on soil composition (moisture and drainage) and depth, wind, and solar access. For *woody species*, there are some additional considerations like root invasiveness and depth, root freeze/thaw, fruit and leaf drop, and self seeding capability.

For the New York Times Tower, the soil moisture and drainage will be controlled with an automatic irrigation system and drainage tile. The wind and solar radiation levels were modeled and compared against known criteria for woody species using the procedure described below.

Solar Modelling:

A 3D computer model of downtown Manhattan was provided by the city planning department (3D models of as-built structures are part of the planning approvals process). The model was validated, calibrated and reconstructed using standard surveying techniques within an eight (8) block radius of the proposed building site (see figure 1.0). Building surfaces were documented during this assessment to model the impact of reflected light. Newtek's **Lightwave 7.0b** was chosen as the most suitable 3D computer application for model construction due to its modeling and rendering robustness and its built in solar modeling capabilities (which accurately models both sun position and intensity). The surfaces of adjacent buildings were applied to the computer model and the proposed structure was constructed from architectural plans of the building. The entire model was placed and oriented in real-world space.

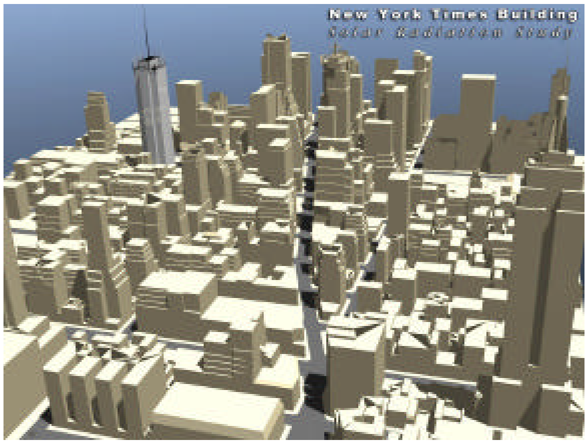

Figure 1.0. *Three dimensional computer model of site. The NY Timees Tower is shown in white.*

We would have liked to compare the shade results from the model with aerial photos or satellite imagery but the team found it difficult to obtain imagery with specific date and time information. In absence of this information, the model was validated by comparing modeled results with actual shadow angles and lengths taken during the site reconnaissance phase. The model showed an excellent match with real shadow angles and lengths in the field.

Five diurnal (daily) simulations were created to assess the available light to both the lower courtyard and upper rooftop garden. The most representative days chosen for the simulation included: (a) the longest day of the year (June 21) and the spring and fall equinoxes (same sun angle on both March 21 and September 21), and (b) dates that were representative of the growing season, namely May 6 and August 6 (same sun angle). The sun was moved through the sky at 1 hour intervals. The result was a snapshot rendering for each hour indicating the degree of shading or sunlight. These hourly renderings were overlaid for the entire day and a diagram was prepared indicating the total number of hours per day that each part of the site was in sunshine. These values were used to generate a composite solar isoline map, which identified, spatially, the total hours of sunshine on the ground plane of both spaces (figure 2.0). This process was repeated by raising the theoretical ground plane of these spaces by 3m to simulate the amount of light available to young tree canopies.

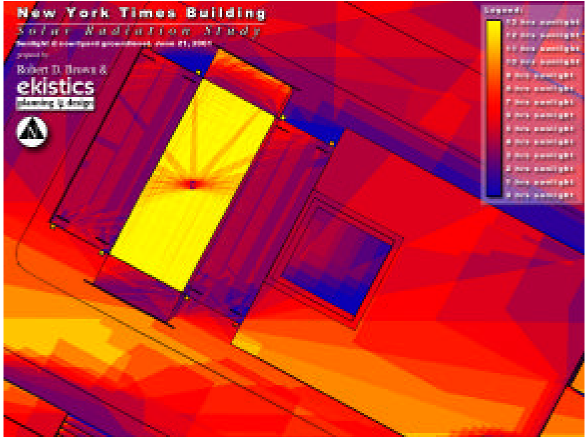

Image 2.0. *Solar map. Colour range shows the number of hours of sunshine per day (June 21).*

The amount of available daily sunshine from the simulation was categorized into 4 groups. The four groups included (a) Full Shade (0-1 hour sunlight), (b) Shade to partial shade (1-3 hours sunlight), (c) Dappled shade to sunny (3-6 hours sunlight), (d) Sun to Full sun (>6 hours sunlight). These groups were compared with known sunshine requirements of plants to identify species that would be expected to survive in each of the different zones of the rooftop and courtyard.

The use of mirrors to reflect sunlight into shady spaces was considered for this application, however, the impact of reflected light on urban plants is not well understood and remains an area for further study.

Wind

The wind levels estimated for the roof garden and courtyard were generated using traditional wind tunnel modelling (RWDI of Guelph, Canada, 2001 and CSTB of Nantes, France, 2001). The results of these studies yielded zones of different wind speeds through the roof gardens for winds of different directions. Based on the findings, the engineers made specific recommendations for the design of a 55' – 95' glass and ceramic impregnated windscreen surrounding the rooftop garden. The screens were designed to prevent wind speeds in excess of 5m/s (11mph) with a frequency of less than 5% of the time. Similarly, for the lower courtyard, summer wind gust speeds of >12m/s (27mph) only occurred between 5-9% of the time. This projected wind speed is insignificant and will not hinder the growth of healthy plants. Other more exposed rooftop applications may require the application of anti-desiccants three times annually to help plants retain moisture.

Root Invasiveness

Trees with invasive or tap roots are not suited for rooftop gardens where they may penetrate waterproof membrane. These include oak, willows, poplar, alders, hickory, walnut.

Soil Depth

Soil depth requirements of woody plants vary considerably from species to species. Early research found that 97% of the roots of woody plants grow in the top 4' of soil (Hicks, 1965). Since the weight of this depth of topsoil is excessive for most rooftop applications (150lb/ft^3 for wet topsoil), soil depths tend to limit the size of trees for rooftop applications. Where soil depths are limited to between 2.5 - 3.5', trees should not be specified larger than 25' to prevent windthrow (Harris and Dines, 1988). Extremely dense leafed trees (Acer platenoides, etc.) also have a greater potential for windthrow than less dense trees. A fully developed plate of roots (360 degrees around the trunk) is also important in anchoring the tree. Therefore, obstructions that would hinder root growth in any direction should be avoided. In artificial conditions, Baker (1984) recommends 2.6'-3.9' of topsoil over an area of 6 square yards for trees, 1.6'-2' of topsoil for shrubs and 6"-10" for grass or annuals.

Since the nutrient reserves of plants grown in artificial conditions can become depleted quite quickly, a well balanced fertilizer program should be established to replenish nutrients on an annual basis.

Plant List

A comprehensive plant list was developed listing candidate plants (partial online database available at www.ekistics.net) for the garden and courtyard. The plants were specifically selected to correspond to the criteria outlined above. The plants were further broken down into 5 sunlight/shade categories. This process allowed the landscape architects to select the appropriate plants based on the appropriate solar maps. The May 6 and August 6 maps were chosen as the representative maps for plant selection. The success of plants growing in full or partial shade in the urban environment is a very uncertain science. Similarly, plants growing in full light or in areas with concentrated reflected light can experience plant scorch on the bark of young trees. Burlapping the trunk for the first year until the tree has adapted seems to provide some degree of protection from scorch. (Baker et al, 1984).

2.0 Thermal Comfort Model

Many earlier human 'comfort' models use windspeed as the primary determinant variable. Discomfort begins to be felt at wind speeds of about 5m/s and discomfort frequency (the amount of time that winds of 5m/s are exceeded) is used to incorporate the metabolic activity. For instance, sitting for a long duration has an exceedance frequency of about 2% of the time, while walking at a slow pace has an exceedance frequency of about 10% of the time. There are some inherent simplicities built into this type of model since comfort in the landscape is based on many more variables than windspeed.

For this study, the COMFA model (Brown and Gillespie, 1995) was used as a basis for comfort estimation. The model required inputs of solar and terrestrial radiation received by a person, wind speed, air temperature, air humidity, and various characteristics such as metabolic activity (sitting, standing, walking, running) and clothing level (t-shirt/shorts, light shirt/pants, windbreaker/pants, sweater, etc.). The 'activity' was determined by the design program (sitting, standing and walking), and the microclimate variables were estimated on an hourly basis for typical summer, fall, and spring days. The model was run for an entire day at the same points used in the wind tunnel study. This assessment gave both a spatial and temporal estimation of comfort for the rooftop garden space and the courtyard space.

Air temperature and relative humidity values, recorded at the nearby Central Park Weather Station, were used directly in the modeling. Wind tunnel studies generated values of 'percentage of full wind' across the site, for each wind direction at various points on the rooftop garden and lower courtyard. Hourly wind values for typical days were multiplied by these wind reduction factors to estimate the typical wind speeds expected at various points in the spaces.

The challenging part of the modeling exercise was to estimate solar and terrestrial radiation across the site. Whereas with the TSR model we only needed the number of hours that a spot was in full sunshine, for the comfort modeling we needed intensity values in watts per square metre (W/m^2). We derived these by interpreting the brightness of the pixels in the solar estimation results. We inserted an imaginary horizontal surface into the sky above the NY Times Tower, and use this as a point of reference. The solar radiation received by this plate should be theoretically identical to that received by the radiometer in the Central Park Weather Station. We used first principles to derive a value of 1000 W/m2 as the maximum direct solar radiation likely to be received in Manhattan. This value became the reference, and all surfaces in the model were compared with this reference value to estimate the amount of solar radiation that was being received. We modeled a 'person' in the simulation using a 0.17m x 0.17m x 1.7m cube which was set in the model to correspond to each of the wind tunnel points. The amount of solar radiation received by the 'people' throughout the day was recorded and used as an input to the COMFA model using the following equation:

$$Sr=sta*(per/gri)*0.8 \quad \text{(equation 1.)}$$

Where *Sr* is the amount of solar radiation emitted in W/m^2, *sta* is the maximum direct solar radiation likely to be received in Manhattan (1,000 W/m^2), *per* is the average brightness level (%) of each side of the cube rendered in the 3D computer modeling (using 15% ambient light), and *gri* is the brightness level (%) of a level surface.

Terrestrial (longwave) radiation values were more difficult to estimate, but fortunately these values typically have less impact on human thermal comfort than solar radiation, wind, and air temperature. Sensitivity tests revealed that the model for estimating terrestrial radiation can be fairly general and still provide adequate results. Terrestrial radiation is emitted by all surfaces on earth, as a function of their temperature. The higher the temperature, the more radiation is emitted. The relationship between temperature and radiation is well established as:

$$TR = \sigma \ (T+273.15)^4 * 5.67x10^{-8} \quad \text{(equation 2.)}$$

where *TR* is the amount of terrestrial radiation emitted in W/m^2, σ is sigma, a factor based on the material, and T is the temperature of the surface in degrees Celsius. This equation works well for most surfaces, with materials such as aluminum and gold having low σ values, and most other materials having σ values close to 1.0. The sky is a special case but is well estimated using the equation:

Trs = SVF x (1.2 x (T+273.15)4 x (5.67 x 10-8))-171

where Trs is the terrestrial radiation from the sky and SVF is the sky view factor. The SVF can be easily determined in a 3D model by placing a camera with a fish eye lens (<12mm) at the desired location. The percentage of visible sky is the SVF.

In order to use equation 2, temperatures of surfaces need to be known. Equation 1 uses air temperature directly. Vertical and horizontal surfaces which are dry and in the shade will tend to be quite close to the temperature of the air. Trees with leaves will also tend to be very close to air temperature in most situations. Surfaces in the sun will absorb and reflect solar radiation as a function of their colour, with darker surfaces absorbing more, and lighter surfaces reflecting more radiation. On dry surfaces, the solar radiation absorbed will be used to heat up the surface. Wet surfaces in the shade will be similar to the wet bulb temperature measured at weather stations, a function of the humidity. After the sun sets, surfaces will cool down at a rate dependent on their thermal admittance as well as their temperature relative to the air temperature. This can be modeled as a simple terrestrial radiation balance to estimate the temperature over time.

A simple approach to modeling terrestrial radiation is to consider just two kinds of surfaces in the sphere of influence that would affect a person: sky, and object. Equation 2 can be used to estimate the terrestrial radiation received from objects using air temperature as a reasonable estimate of the surface temperature of objects. Equation 1 can be used to estimate radiation received from the sky. Sky view factor was then used to determine the percentage of the sphere of influence that was affected by each of the two amounts of radiation.

$$Tlr=(0.5*((sky*svf)+(obj*(1-svf))))+(0.5*gro)$$

The terrestrial radiation that would be received by a person standing at each point in the grid was calculated for each hour and the resulting data were exported as an Excel spread sheet.

When all the variables for each modeled point were exported to Excel, the COMFA model calculated an estimate of the comfort level for each grid point, at each point in time. The output from COMFA was in W/m^2, and these values were interpreted according to the categories suggested by Brown and Gillespie (1995).

Sensitivity tests revealed that the models were most affected by small changes in solar radiation levels and wind speeds, while differences in terrestrial radiation and air humidity had less effect.

Test results were run to estimate the hourly comfort (figure 4) at a variety of locations in the courtyard (figure 3) for various days through the year. The model provides a synopsis of hourly comfort for each location in the courtyard and rooftop garden. This information will help the designers to consider location specific strategies to improve thermal comfort.

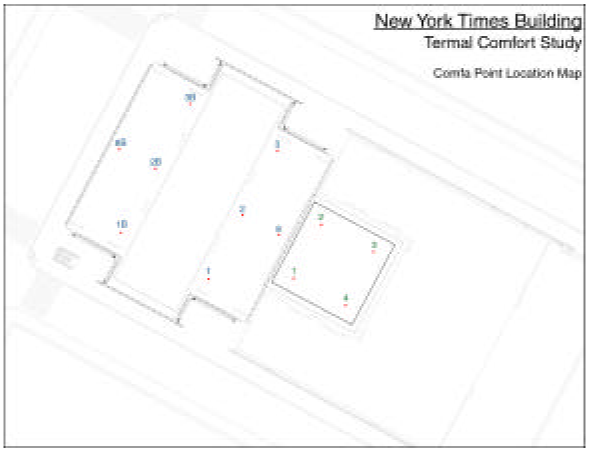

Figure 3. *Location of COMFA model points.*

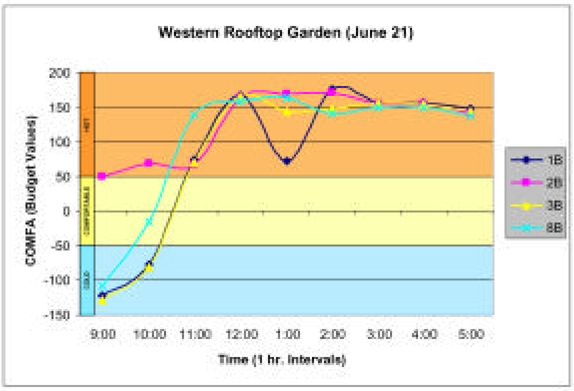

Figure 4. *Western rooftop garden comfort (June 21st).*

Data Requirements

The following data sets were required to complete the modeling and simulation:

1. Identification of a nearby weather station.
2. Daily minimum air temperatures, preferably from both stations, but at least from the ground station, for November to March for a 'cold' year (to determine extreme conditions),
3. Hourly air temperature for a range of days throughout the year (total of eight: one sunny and one cloudy day for each season),
4. Summarized wind data (normals) identifying % of time that the wind typically blows from each direction (number of directions to match that used in the wind tunnel studies),
5. Hourly solar radiation data for sunny days (for any year) on December 21, June 21, March 21 and/or September 21, May 6 and August 6,
6. Hourly air temperature, wind speed and direction, air humidity, solar radiation, and terrestrial radiation (if recorded) for two days (one sunny, one cloudy) from each season (any year).
7. Satellite image of study site on clear sunny day of known date and time.

Steps

A. Tree Species Recommendation Model:

1. A 3D computer model of buildings and site (existing and proposed) was constructed and ground-truthed.
2. The solar simulator was run at hourly intervals for the test days (June 21, May 6 and August 6, March 21 and Sept 21) at both ground level and 3m above ground level height.
3. The shade results were validated using shadows cast on the actual site at a known date and time..
4. A total of 6 composite solar maps (the three different dates at the 2 different elevations) showing the hours of sunshine received for each test day was prepared.
5. A wind tunnel study was undertaken to determine the windthrow potential and moisture depletion potential of plants.
6. A comprehensive plant list was prepared with suitable plants for each of 5 different light conditions (full shade to full sun).

B. Thermal Comfort Estimation Model:

1. Typical days were selected for each season and hourly data on air temperature, air humidity, wind speed and direction, solar radiation, and terrestrial radiation were acquired from a nearby weather station (Central Park).
2. Wind tunnel simulations were used to identify wind reduction factors across the site for each wind direction. Data were recorded as 'percentage of full wind' values across site.
3. Solar simulator was run for each of the six typical days to yield solar radiation received by a modeled person at various locations across the site.
4. Sky view factor was determined for the test locations.
5. Grids were exported to spreadsheet. COMFA was integrated into the Thermal Comfort Estimation model, which accessed appropriate layers and estimated comfort level of person at each point in the grid for each hour of the test.
6. Results were mapped using isolines to illustrate the areas that are expected to be most comfortable at

test times.

Application

The New York Times Tower, proposed for Times Square, New York, will have a rooftop garden (on the 53rd storey) and an urban courtyard (at ground level) as centerpieces of the new development. The human comfort and plant survivability of these spaces was assessed to ensure that the final landscape design responded to the microclimate conditions in these spaces.

This study was undertaken to interface between wind tunnel studies conducted by RWDI Ltd. (Guelph, Canada) and CSTB Ltd. (Nantes, France) and the landscape architects responsible for the design of the gardens, HMWhite Site Architects (New York) and Cornelia Oberlander (Vancouver, Canada). Architects for the building were Renzo Piano of Paris, France and Fox and Fowle of New York.

Summary and Recommendations

This study demonstrated that 3D computer modeling, which has been traditionally used just for visualization purposes, can play a critical role in the deterministic modeling of outdoor environments. In particular, it can play a significant role in microclimate modeling and human thermal comfort modeling. The results of this exercise provides the landscape architects with an understanding of future environmental conditions and a detailed list of plants which has the best potential to survive in these spaces. This knowledge provides them with the foresight to find the best design solution for these spaces in response to future environmental conditions.

Software Used

Lightwave 7.0b, Photoshop 6.0, Microsoft Excel XP,

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