Daylighting in a Hot Arid Area

by

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ABSTRACT

The availability of daylight, including diffused sky light and direct sunlight, in urban open spaces is an important environmental factor in designing and regulating buildings in high density urban areas. The establishment of a scientific and quantitative basis to evaluate the daylighting impact of a building has been one of the major concerns among daylighting and city planning communities.

This study on daylight initially investigates methods to predict the daylight levels in urban environments. The methods to deal with complex urban geometries and their optical properties were explored. A computer-based illumination model for daylight in urban environment was developed adopting numerical methods. The direct components from the sky were estimated by the finite elemental area method, and the reflected components were approximated by the recursive iteration method.

Using the model, analyses of daylight availability in the downtown Phoenix area were conducted . Urban zoning parameters were explored with respect to their potential to the impact on the daylight utilization in commercial buildings in the target area. A special emphasis is given on analyzing the performance of inter-reflected light in urban open spaces and in commercial building interior spaces.

INTRODUCTION

During the past two decades, daylighting R&D in the United States can be characterized as driven primarily by energy or economic concerns. Conserving electric lighting energy by utilizing daylight in commercial buildings has been studied extensively with respect to various window and space designs, lighting control systems, and the interaction with mechanical HVAC systems. Reducing electrical peak loads was also investigated in order to reduce initial building costs through smaller HVAC systems as well as to reduce electrical costs during operation.

Although daylight provides an important opportunity for energy savings and increasing lighting quality in commercial buildings, it is difficult to predict for the build-up urban surroundings. To date, the daylight prediction tools available have not allowed for the effects of complex surroundings properly. As a result, research on daylighting benefits has tended to only to low-density situations where there are no significant external obstructions. In reality, however, commercial buildings in high-density urban areas function as mutual obstructors for natural light, air, and view.

Urban land is under constant pressure for higher usage. Development on urban land is oriented increasingly toward high-density, high-rise structures. Towering buildings create street canyons that reduce available daylight not only inside the buildings adjoining the canyons, but also in streets and open spaces. This crowding of tall buildings raises a series of urban zoning issues.

The livability of open spaces is much affected by environmental factors, including solar radiation. Ambient temperature, humidity, wind velocity, and radiant energy from the sun all directly affect the potential for thermal comfort in a space. Light level and distribution affect the lightness or gloominess of an outdoor space, which in turn influence public use. In urban downtown areas the availability of solar radiation in and around buildings has been endangered by the increasing number of high-rise buildings. This has in some instances prompted strong reactions from municipal organizations.

This paper initially introduces an daylight illumination model, CITYLIGHT [1], devloped for analyzing daylight levels in urban outdoor spaces, and investigates daylight availability in and around a building located in the downtown Phoenix area. Indoor daylight levels in a prototypical office building have been estimated under a variety of urban conditions using a daylight illumination model SUPERLITE 1.0 [2].

CITYLIGHT

The overall structure of the model CITYLIGHT for daylight in urban outdoor environments is composed of four major calculation modules: daylight availability, building geometry, direct (initial) component, and reflected component. The overall structure of the model is shown schematically in Figure 1.

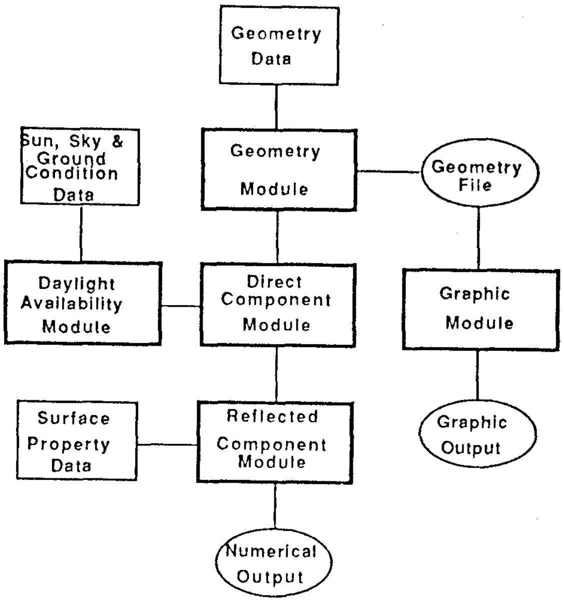

Figure 1: Overall structure of CITYLIGHT.

The geometric module processes geometric input data describing buildings in a target space. The locational, orientational, and dimensional attributes of each surface (a four-sided polygon) of the buildings that constitute the space are specified with a coordinate system local for each surface.

The surfaces of buildings are then subdivided into a number of subsurfaces, whose resolutions are specified by users depending on their desired accuracy. The geometric attributes of a subsurface, such as its area and the X,Y,Z coordinates of its nodal point, are also calculated.

Another major function of the geometric module is to determine the visibility relationships between all nodes in the environment, which requires several processes. In principle, the visibility relationship between any two nodes can be determined by view checks to discover any obstructions between them. However, implementing this operation for all nodes in the environment is time-consuming due to the large number of intersection checks required. In order to reduce the number of checks and thus to increase calculation efficiency, several algorithms have been developed [3]. The octtree algorithm [4-5] applied to ray tracing models, recursively subdivides the boundary space that encompasses all the objects in an environment into a number of cubes, called "voxel", of decreasing volume. The view checks for a given line of sight are made with respect to the voxels, not with respect to the surfaces of objects. If the line of sight pierces empty voxels, the view for the line is clear. However, if the line vector pierces a voxel that contains objects, this voxel is further subdivided into sub-cubes (smaller voxels), and more intersection checks are performed between the line vector and the sub-cubes. By repeating this process until the size of a voxel is smaller than a specified criterion, the visibility of a given line of sight is determined.

CITYLIGHT determines visibility relationships in part by adopting the idea of the line-to-volume intersection check of the octtree algorithm. First, a bounding volume encompassed by three sets of two parallel planes is generated for each building (see Figure 2). Each plane is parallel to two of three (X,Y, or Z) orthogonal axes of the global coordinate system so that the plane equations for the bounding planes can be expressed simply by a constant. For instance, for a plane that runs parallel to Y and Z axes, its plane equation is x=c, where c is a constant. Having simplified expressions for the plane equations reduces the computation time for solving two simultaneous equations of a plane and a line to determine their intersection point. The constant c is either a maximum or minimum X,Y,Z coordinate of the vertices of a building.

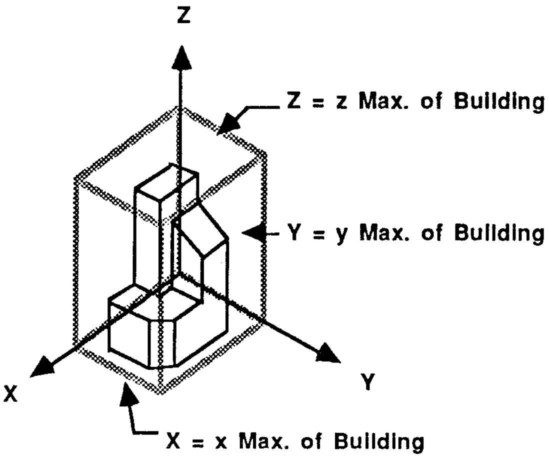

Figure 2: Bounding volume.

Next, given a line that connects two nodes, the relationship between the line and the bounding volume is checked to see if the line pierces any bounding volume. If the line does not pierce a bounding volume, the surfaces of the building in the bounding volume will not intersect the line. Therefore, no further intersection check is necessary for the volume. However, if the line vector pierces a bounding volume, it is necessary to check further to see whether any surface in the volume obstructs the vector. This intersection check is made again by solving two simultaneous equations for the line and the surface (plane). Once the intersection point is obtained, it must be tested to see whether it is located within the boundary of the polygon: if the intersection point is outside the polygon, the polygon does not intersect the line; if the intersection point is within the boundary of a polygon, the polygon intersects the line.

Once the value of node-to-node visibility, 0 (when obstructed) and 1 (when clear), is found, its congruency with neighboring visibilities is evaluated to see if they can be grouped together. CITYLIGHT uses three levels of grouping: 1) node-to-node, 2) node-to-line, and 3) node-to-surface. When all nodes in a surface are visible from a node, they are entered in the node-to-surface counter, and the elemental node-to-node visibilities are discarded. This count functions as an address indicating the locations of a surface and a volume, these being stored in separate lists of surface and volume names.

The second module of CITYLIGHT determines the availability of daylight at a geographical location. First, the position of the sun is determined for a specified time of day and time of year. Three types of sky conditions can be modeled: uniform sky, CIE standard overcast sky, and CIE standard clear sky. The zenith luminances of uniform and overcast skies are estimated by the equation expressed as a function of sun position only.

When a clear sky condition is specified, so too is the condition of the atmosphere in terms of water vapor content and angstrom's turbidity coefficient. Based on these atmospheric conditions and the position of the sun, the direct normal solar illuminance, the zenith luminance, and the luminances of the sky are determined. Finally, by integrating the luminance of the entire sky vault, the diffused horizontal luminance from the sky is calculated.

The third module calculates direct illuminance levels within an urban environment due to the sun, the sky, and the ground. For a clear sky condition, visibilities of the sun are checked at all nodal points within the environment, and if the sun is visible from a node, the direct solar illuminance is assigned, taking into account the directional cosine between angle of incidence and the surface normal vector of the node. If a surface is specularly reflective, the angle of reflection and the amount of reflected illuminance must be stored for a later calculation of the interreflected component. On the other hand, if a receiving surface is diffusive reflective, only the illuminance level is stored.

The direct illuminances from the sky and the ground on diffusive surfaces are calculated by first determining the skyline and the ground-line seen from each node, and then integrating the light flux originating from visible sky patches for sky components, and those originating from the visible ground patches for ground components.

When specularly reflective surfaces are present, the directional distribution of reflected flux must be determined and stored at the same time as the direct illuminances from the sky and the ground are calculated. This again prepares for estimating the interreflected flux in the succeeding module. To accommodate this necessity for determining incident light flux and for storing directional distributions of reflected flux, a unit hemisphere is generated on every node of a specular surface. The unit hemisphere is subdivided into a number of elemental patches in such a way that their projected areas on the base of the hemisphere are equal, a fact that greatly simplifies and stablizes the integration of luminance over a 2π solid angle (Note that the equal projected area represents the equal form fact).

On specular surfaces, the unit hemisphere and its patches at the nodes serve two primary functions: 1) determining incident light flux and 2) storing directional distribution of reflected flux. When determining incident light flux, a node under the hemisphere can be regarded as a sink of light flux, whereas the sky, the ground, and the objects around the 2π hemisphere over the node became sources of light. The patches on the unit sphere effectively serve as the entrances of incoming flux to the sink (node). To identify the source seen through a patch from the node, a vector that originates from the node and pierces through the center point of the patch is generated for each patch of the hemisphere, and the object that the vector hits becomes the source of light for that patch. If the vector hits no object, it will point either to the sky (when the Z component of the vector is positive), or to the ground (when the Z component of the vector is negative).

Having identified the objects seen through the patches, the elemental illuminances at a node due to each patch can be obtained simply by multiplying the luminances of the objects by the form factor associated with the patch, which is a constant (= 1/number of patches).

The distribution of reflected flux on a specular node is also numerically determined based on the patches of the unit hemisphere. Specifically, the patches on the hemisphere over a node (source) now function as the exits for reflected flux to surroundings. The vector from the node toward the center points of the patches represent the directions in which light flux exiting the patch is calculated. Thus, the directional distribution of the reflected flux of a node is calculated only in those discrete directions toward its 2π hemisphere. Here, the directional distribution of reflected flux due to multiple incident light fluxes is obtained based on the additive property of light: The directional distribution of reflected flux due to two incident light fluxes is the directional sum of two directional distributions due to each incoming light flux.

The fourth and final module of the program calculates interreflected light flux. Using the visibility relationships established in the geometric modules and the distribution of initial reflected flux due to the first excitation of direct components, this module traces the flux exchange between building surfaces to obtain the interreflected component.

The accuracy of predictions using CITYLIGHT depends on several key parameters. The resolution of sky subdivision is the primary parameter for the direct components. For reflected components, the resolution of the surface subdivision and the patches of unit hemisphere over specular nodes, and the number of iterations for recursive integration determine the predicted accuracy. In the design/coding of CITYLIGHT, these parameters pertaining to the accuracy of the calculation are designed to be controlled by the users. In the future, some default recommended values will be assigned to the model for users in architectural or urban design practices. In this way, users will be able to determine and obtain their desired level of accuracy based on their interest and purpose of using the model.

The validation of CITYLIGHT has been done through internal process checks, comparison with analytical results, and comparison with scale model testings. The validation tests of CITYLIGHT through internal process checks show that the model produces proper intermediate results from key subprocesses. The comparisons with scale model testings indicate that the model provides proper overall performance [1]. In the future, the validation of the model should be made by comparing its results with measured data taken in actual urban areas. Due to the methodological limitations of handling various uncertainties in field measurement comparisons, this procedure was not included in the scope of this study.

ZONING ENVELOPE OF PHOENIX

This study's analysis of the availability of daylight in urban open space was carried out for a street canyon configuration. The prototype street canyon model was created assuming that the downtown Phoenix area was developed fully in accordance with the current zoning regulation imposed on the area. Thus, the configuration represents the zoning envelope of the area, not the building envelope created by individual buildings, which are difficult to predict. Figure 3 shows the current building configuration of Downtown Phoenix area, and Figure 4 demonstrates the zoning envelope of the area.

The zoning envelope produced by the zoning regulations of the city of Phoenix are as follows:

1. The size of a block is 250ft by 250ft, typical dimensions of a block in the downtown Phoenix area.

2. The width of a street is 80 ft.

3. The city has no regulation regarding to the height of street wall. In this study the street wall is assumed to be150 ft high. Five feet of setback for every 50 ft rise of the building height above the street wall is required.

4. The maximum height of the zoning envelope is 250 ft above the ground due to the height regulation in the area.

5. The surface reflectance of the buildings is a uniform 50%.

6. The reflectance of the ground is assumed to be 20%.

7. The climatic conditions of the test site are those of Phoenix, Arizona, whose latitude is 32 degree North and latitude 144 degree West.

8. The time of simulation is noon, December 21, which represents the lowest solar altitude angle of the season.

9. The reference points tested transect the street at midblock.

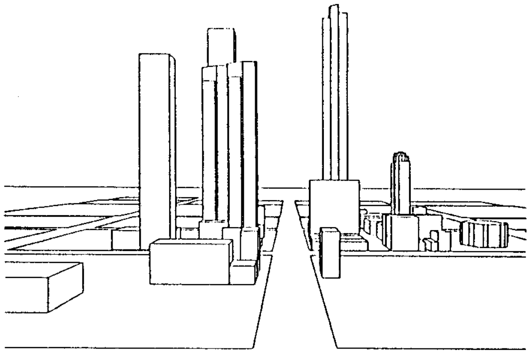

Figure 3: Existing Building Configuration in the Downtown Phoenix Area

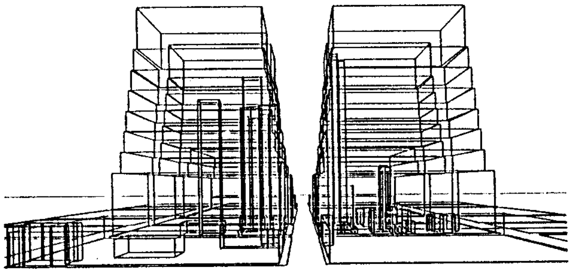

Figure 4: Zoning Envelope of the Downtown Phoenix Area

Figure 5-a and 5-b show daylight illuminance levels on the street level and on the vertical surfaces of the zoning envelope. Figure 5-a shows asymmetric distribution of illuminance on the street: The daylight levels on the western half of the street are much higher that those of the eastern half. This is due to the reflected flux from the sun on the western half of the street. The figures also reveal that reflected components contribute significantly to the total daylight levels than sky (direct) components.

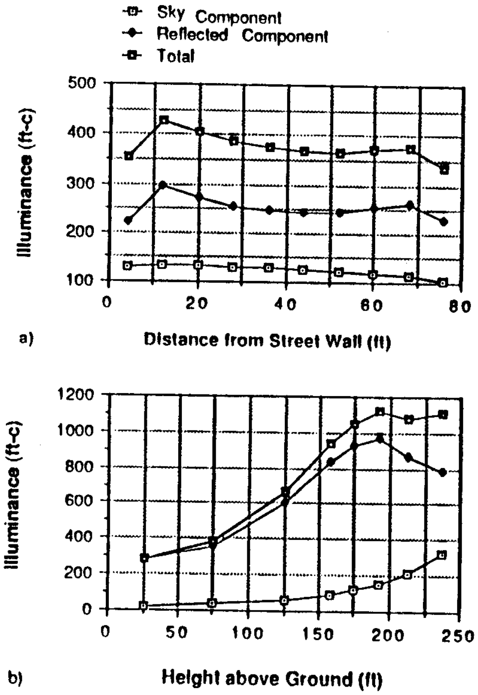

Figure 5: a) Daylight levels on the street. b) Daylight levels on a vertical surface

DAYLIGHT LEVELS IN A BUILDING

Daylight levels in a room facing street canyon are affected by its external conditions, fenestration systems and room geometry and surface reflectance. Using SUPERLITE 1.0, the daylight levels in a room 20 ft wide, 20 ft deep and 10 feet high was calculated. Figure 6 compares daylight levels in the test room located on a range of heights above the ground. The figure indicates that daylight levels in the building is very sensitive to heights up to 100 ft, but it reaches a point of saturation above the height.

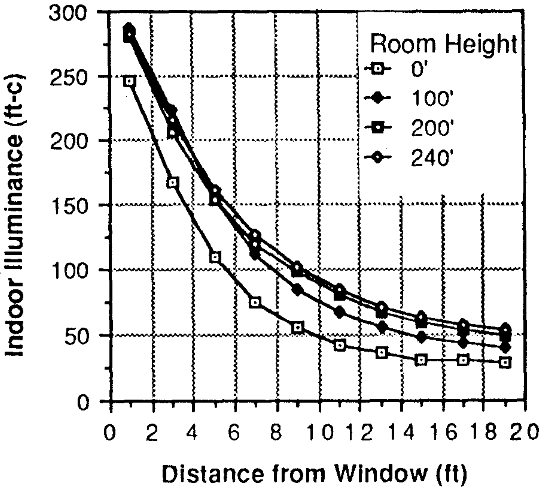

Figure 6: Daylight levels in rooms located on various heights above the ground

EXTERNAL SURFACE REFLECTANCE

The surfaces of adjacent buildings around a target environment on the one hand serve as obstructors that reduce the view to the sky. At the same time, the external surfaces also function as sources of reflected light flux originating from the sun, the sky, and the ground. When the sun is present, the luminances of sunlit building surfaces on average building surfaces that have 20% reflectance can be higher than that of the sky. What this means is that those sunlit areas add more light to a space than would the sky that the surfaces obstruct.

Under an overcast sky, when light in a street canyon is needed most, surfaces of the street canyon reflect only the light flux originating from the sky and the ground. Under those conditions, the luminances of building surfaces are lower than that of the sky.

Figure 7 compare daylight levels in the test room for a range of diffusive surface reflectances. The figure indicates that the daylight levels increase significantly as surface reflectance increases. The significant increase of reflected components under clear sky conditions are primarily due to the presence of sunlight.

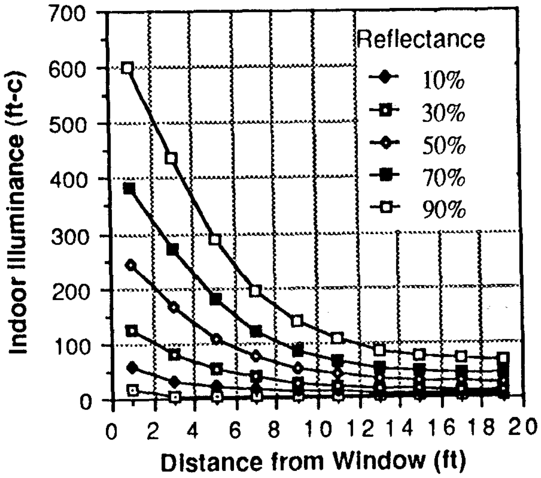

Figure 7: Daylight levels in the test room with various external surface reflectances.

CONCLUSIONS

One of the most significant results from the analyses discussed in this paper is the importance of building surface reflectance on the total daylight levels. The analysis indicated that the texture of the building surfaces is an extremely critical factor influencing daylight levels in urban environments.

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