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Visualization Techniques in a Building Potential Simulator Using Sunlight Access Control

Pablo Colossi Grazziotin
Instituto de Informática
UFRGS – Porto Alegre – Brasil
pablo@inf.ufrgs.br

Carla M. Dal Sasso Freitas
Instituto de Informática
UFRGS – Porto Alegre – Brasil
carla@inf.ufrgs.br

Benamy Turkienicz
Faculdade de Arquitetura
UFRGS – Porto Alegre – Brasil
benamy@portoweb.com.br

Fernando O. Ruttkay Pereira
Faculdade de Arquitetura
UFSC – Florianopolis – Brasil
feco@arq.ufsc.br

Abstract

This paper presents the use of a technique known as solar envelope in the simulation of building potential of urban plots as well as the improvement of 2D and 3D visualization techniques of simulation results. The consideration of sunlight access in urban planning fulfills basic requirements for improving the quality of buildings regarding thermal comfort. The work has improved an existing decision support system, CityZoom, which provides an environment where several performance models can be used in an integrated way for urban planning. One of these models is BlockMagic, where insolation can be simulated along with Master Plans rules, seeking to maximize both building potential and sunlight access. Besides the adoption of the solar envelope concept in the simulation, 2D and 3D visualization techniques were developed in order to show sun-path diagram, sky vault obstruction due to neighboring buildings, and 3D view with shadows obtained from the buildings simulation.

Keywords

Building simulation, sunlight illumination, sun path simulation, shadows, visualization techniques

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1. INTRODUCTION

Designing buildings in accordance to cities Master Plan's rules is a complex and time demanding process. A city's Master Plan determines the maximum area that can be built in an urban plot, i.e. the plot's building potential or plot ratio. The use of computer-based tools to simulate those buildings can seriously improve the task.

Access to sunlight is a desired characteristic in any building project, as it provides energy saving and improved life quality environments. It is essential to consider the sun during the design phase, in order to achieve best benefits from the availability of solar radiation in and around the building. The inclusion of these factors in the design process can have great impact over the land use, built density, and urban land value.

There are good commercial tools for building design purposes, capable of assisting architects in many ways, including sunlight access issues.

RADIANCE [Radiance] is a ray tracing program that enables accurate and physically valid lighting and day lighting simulations. It was originally developed for UNIX, and then integrated into the ADELINE [Adeline] software which runs on standard PCs. Using input data from common CAD programs and special converters, the framework can simulate daylight and generate:

- physically exact photorealistic views of the building,
- both luminance and illuminance distributions on all component surfaces,
- visual comfort evaluations.

ECOTECT [Ecotect] aims to address environmental design principles during the most conceptual stages of design. It provides visual and analytical feedback from the sketch model, progressively guiding the process as more detailed design information becomes available. It features a 3D modeling environment and tools for:

- interactively viewing shadows, sun penetration and reflections,
- displaying overshadowing on stereographic or orthographic sun-path diagrams,
- displaying shadow profiles for any date/time range,

- solar exposure calculations for optimizing passive solar design techniques and photovoltaic panels.

However, these tools fail in considering both the Master Plans and the sunlight issues in an integrated environment. Even though structural, climatic, visual, energetic, and even legal aspects are independent, they are interactive. An energy-efficient modification in the design could result in negative structural consequences, or even in illegal buildings regarding Master Plan's rules. Therefore, an integrated design environment would be of high value for architects, builders, city advisors, or any person interested in these relations.

CityZoom [CityZoom] is a decision support system for urban projects, with a module capable of performing simulations based on Master Plan's rules, BlockMagic.

Solar envelope is a device for sunlight access control based on boundaries derived from the apparent sun path. Buildings within these boundaries do not cast undesired shadows over their neighborhood, assuring urban solar access for both energy and life quality. Insolation can be simulated along with Master Plans' rules, seeking to maximize both building potential and access to the sun and its benefits.

The work reported here resulted from the integration of sunlight access parameters to BlockMagic, making for the simulation of edifications with optimal building potential use and solar radiation availability.

The three-dimensional interface was improved in order to provide a realistic environment with shadow casting between the buildings along the day and the year, based on simulation results. New methods for results visualization were also developed, such as solar obstruction masks (sky vault view) and sun-path diagrams.

The paper is organized as follows. Section 2 presents CityZoom framework, its data classes and modules, with special attention to BlockMagic. Section 3 explains the solar envelope's properties, equations and application. The integration of the solar envelope concept to BlockMagic, and the developed visualization methods are shown in section 4 and 5, respectively. Section 6 presents the conclusions and poses possible future work.

2. CITYZOOM OVERVIEW

CityZoom [CityZoom] is a decision support system for urban planning. It is currently being developed as a research project in the Laboratório para a Simulação e Modelagem em Arquitetura e Urbanismo (SIMMLAB/ UFRGS) in collaboration with the Laboratório de Conforto Ambiental (LABCON/UFSC).

CityZoom provides an environment where several performance models can be used in an integrated way for improved urban planning. Each of these models operates on different entities of an urban hierarchy (Figure 1), affecting all the related ones. The modules currently available in CityZoom are presented in Figure 2.

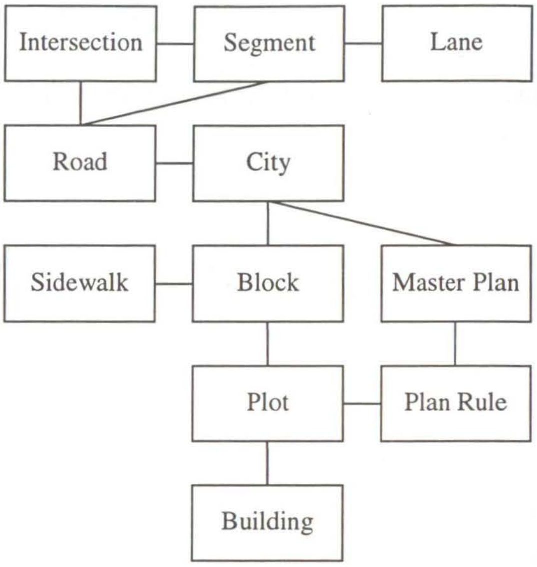


Figure 1: CityZoom city hierarchy

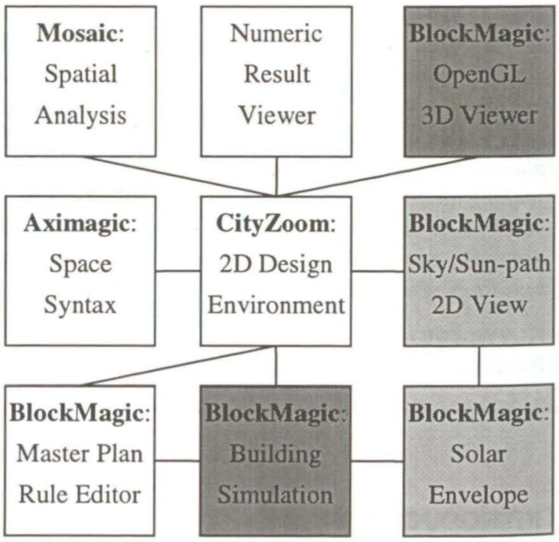


Figure 2: CityZoom modules

The central module is CityZoom 2D Design Environment, which provides tools for graphically designing the basic distribution of blocks and plots in a city, and works as a main interface for all other modules, storing all the city data.

Aximagic operates over axial data, performing Space Syntax analysis, which provides information about road's topological relationships.

Numerical data can be obtained from city's geometrical elements (for example, block area) or explicitly associated to them (for example, population per building) using the design tool. These data can be queried using the Numerical Result Viewer.

Mosaic, which is a Spatial Analysis tool, can generate color maps directly from city data, or from arithmetic operations on pre-generated maps.

BlockMagic is CityZoom's model for simulation of the building potential of urban plots, based on the Master Plans' rules of a city specified with the 2D design tool. It can swiftly generate large sets of buildings in the most different urban scenarios, or validate user-built edifications.

BlockMagic is implemented by four modules, two of them being the result of the present work (those depicted in light gray in Figure 2):

- BlockMagic – Solar Envelope, which performs solar envelope calculations (Section 3.2);
- BlockMagic – Sky/ Sun-path 2D View, responsible for generating sky vault obstruction visualization as well as sun path calculation and visualization (Section 5.1).

The two other modules (in dark gray, Figure 2) were already part of CityZoom, and were adapted as follows:

- BlockMagic – Building Simulation: insolation was introduced in the simulation process through the use of solar envelope (Section 4);
- BlockMagic – OpenGL 3D Viewer: the 3D visualization engine was modified to support generation of realistic shadows in real time (Section 5.2).

CityZoom provides not only a design and simulation environment, but also a visualization tool, allowing both a quantitative and a qualitative analysis of existing and simulated buildings. This is obtained through the Numeric Result Viewer, capable of assessing data in multiple levels and BlockMagic three-dimensional viewer, allowing interactive navigation in a virtual representation of the current scenario. Numerical data can be queried for the whole city, or selected blocks, plots, or buildings; some interest attributes are total area, built area, building use, occupation rate, and average floor number.

3. SOLAR ENVELOPE

The solar envelope [Knowles00, Pereira01] is a geometric representation devised to facilitate the control of the amount of sunlight received by buildings in an urban area. It can be used to regulate the construction of new buildings within imaginary borders derived from the apparent sun path. Buildings contained inside the envelope do not cast excessive shadows over their neighborhood during critical periods of sun access (for example, during the winter).

The solar envelope is a construct of space and time: the physical boundaries of surrounding areas and their assured period of sunshine access. The envelope's final size and shape is defined by the way these measures are set.

3.1 Solar Envelope Properties

First, the solar envelope avoids undesired shadows above designated boundaries along neighboring property lines; these boundaries have been called *shadow fences*. The height of shadow fences can be set according to any number of surrounding elements such as windows, privacy fences, or party walls. Their height may also be set by adjacent land uses with, for example, housing demanding lower shadow fences than commercial or industrial uses. Different heights of shadow fences will affect the size and shape of the solar envelope.

Second, the envelope provides the largest volume within time constraints, called *cut-off times*. The envelope accomplishes this by defining the largest theoretical container of space that would not cast shadows off-site between specified times of the day. Greater periods of assured solar access will be more constraining on the solar envelope. Cut-off times that are specified very early in the morning and late in the afternoon will result in smaller volumes than would result from later times in the morning and earlier times in the afternoon.

3.2 Solar Envelope Implementation

There are three approaches to implement the solar envelope model. Knowles' [Knowles00] approach is based on the apparent sun path and the specific periods (during the year) for which a certain amount of sun light is desired. Shaviv and Capeluto [Shaviv00] defines constraints in terms of buildings' maximum height and windows' minimum height, so the intersection of each solar envelope determine the amount of sunlight received by the buildings' windows. Pereira's methodology [Pereira00] was developed based on the desirable solar radiation considering biological requirements and local climate. Moreover, this approach considers the Brazilian climate, hence is more suitable to our goals, and is already a computer-oriented solution.

The main criterion used by Pereira is the balance of the different requirements of solar radiation over the year, translated into the concept of *desirability and undesirability of solar radiation*. His solution lays in relating three different information sources:

- *climatic conditions*: represented by the external air temperature and solar radiation on vertical planes;
- *psycho-physiological requirements* from people subjected to variable climatic conditions;
- *geometry*: represented by the insolation and geometric relations within the built environment.

Pereira represents the user satisfaction/dissatisfaction with the incident solar radiation by a ponderation system of the solar radiation as a function of the difference in magnitude between the *external air temperature* and *neutral temperature*, translated into *ponderation factors* (PF). The monthly neutral temperature is obtained from the monthly mean temperature through the following equation:

$T_n = 11{,}9 + 0{,}543\ t_m$ [Humphreys78]

where: T_n = neutral temperature [°C]

t_m = monthly mean temperature [°C]

The ponderation factors are obtained by the following expression:

$PF = | (T_{air} - T_n) / 2 |^{\alpha}$ [Szokolay80]

where: T_{air} = external air temperature

$^{\alpha}$ = exponent (warm = 1.6 and cold = 1.0)

The PF will be negative (insolation is undesirable) when the air temperature is higher than the neutral one, and positive (insolation is desirable) in the other way.

The integration of the climatic condition and the psycho-physiological requirements is obtained through the product of PF by the solar radiation (direct and diffuse) values on each facade throughout the year. The solar radiation can be estimated by the equation:

$I_T = I_b R_b + I_d ((1 + \cos\beta) / 2) + I \rho_g ((1 - \cos\beta) / 2)$ [Duffie92]

where: I_T = total radiation in the oriented surface,

I_b = radiation's beam component,

R_b = beam radiation ratio in the oriented plane in relation to the measured plane,

I_d = radiation's diffuse component,

β = slope, equal to 90° since the surface is vertical,

I = total solar radiation measured in a horizontal surface,

ρ_g = ground reflectance.

The product of the radiation by the PF is called *pondered radiation*, and the values are plotted on the apparent sunpath diagram for a given latitude (Figure 3).

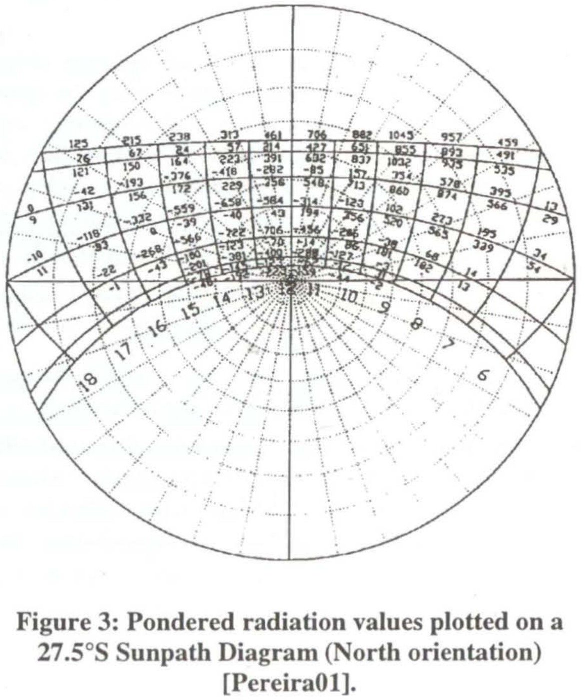


Figure 3: Pondered radiation values plotted on a 27.5°S Sunpath Diagram (North orientation) [Pereira01].

Using the stereographic projection, the built environment can be plotted onto the sun-path diagram, resulting in the sky vault obstruction (Figure 4).

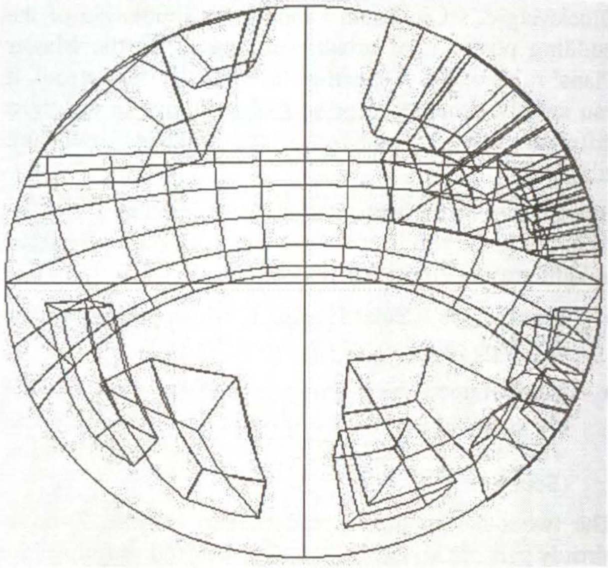


Figure 4: Sky vault obstruction example [Pereira01].

To integrate the geometry and the other information sources, sun-path diagrams are built with the values of *pondered radiation* for each desired vertical facade orientation (Pereira considers 8 orientations). These values are then summed for each of the orientations to estimate the degree of obstruction produced by the surroundings which will provide the best balance (maximum of desirable radiation and minimum of undesirable radiation). This is done by considering the environment as a continuous wall with variable height (0 to 90 degrees of obstruction angle); the final sum values for each level of obstruction expresses the quality of the obstruction related to its thermal performance according to the available solar radiation in a given climatic condition.

Finally, the idea would be to exclude from the urban environment the undesirable radiation and accept the entire desirable one. It is not possible to have a complete optimization, so some initial criteria are used to define the obstruction angles to be used on each orientation:

- positive balance of pondered radiation through the whole year;
- positive balance for the equinoxes (March and September);
- 1.5 to 2 hours per day of insolation duration during the winter.

Obstruction angles are then chosen in order to satisfy at least two of the listed criteria (Table 1).

Applying these angles to the plot edges provides a set of geometrical limits derived from the pondered radiation balance evaluation. The result is the largest volume a building can occupy allowing sunlight access to adjacent neighborhood, called *solar envelope* (Figure 5).

Orientation	Obstruction Angle
N	40-45
NE	45-50
E	50-55
SE	55-60
S	55-60
SW	55-60
W	60-56
NW	55-60

Table 1: Obstruction angle for each orientation in Florianópolis, SC, Brazil [Pereira01].

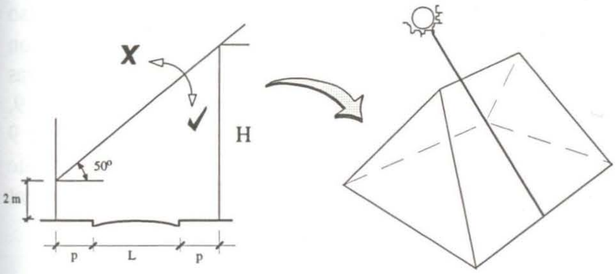


Figure 5: Application of obstruction angles for defining the *solar envelope* [Pereira01].

4. USING THE SOLAR ENVELOPE IN THE SIMULATION OF URBAN BUILDINGS

BlockMagic, as explained in section 2, uses Master Plans' rules as input parameter for simulating the building potential of urban areas. However, cities' Master Plans fail in considering solar radiation among their regulations. The solar envelope is used to improve these simulations. Each plot is simulated individually, following the simulation steps below:

- a starting building volume is defined, with height equal to one floor and other dimensions matching the plot ones;
- using the solar envelope's obstruction angles table, the plot's facades' orientation, and the building height, a minimum setback is calculated for each plot facade;
- the setbacks generated from the solar envelope are compared to the Master Plan's minimum setback rules, and the larger ones are applied to each side of the starting building;
- maximum occupation (slab area to plot area ratio) Master Plan's rule is applied to the building;
- maximum use (built area to plot area ratio) Master Plan's rule is applied to the building;
- repeat the previous steps for two floors and up to the maximum number of floors allowed in the Master Plan, saving the desired parameter for comparison if it was possible to create a building with that set of rules.

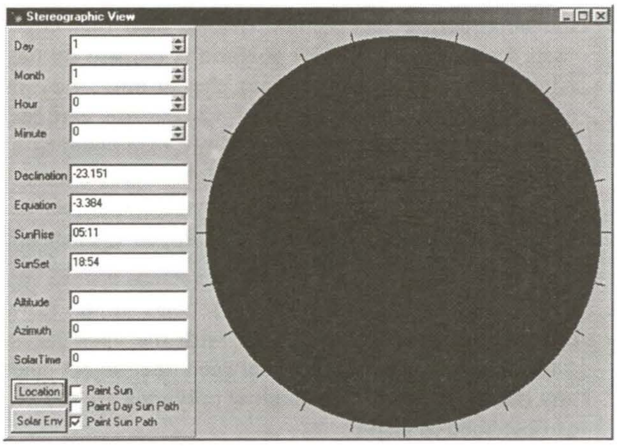
Several parameters can be simulated or maximized, such as: built area (use), slab area (occupation), number of floors, front size, and side size. Regardless of the desired building characteristics, the generated volume will be contained within the solar envelope, therefore not casting undesired shadows over its neighborhood.

5. RESULTS

In order to computationally implement the solar envelope and to ease the understanding of the results, new visualization methods were required. Some 2D visualization techniques were developed, and the existing 3D engine was upgraded.

5.1 2D Visualization Techniques

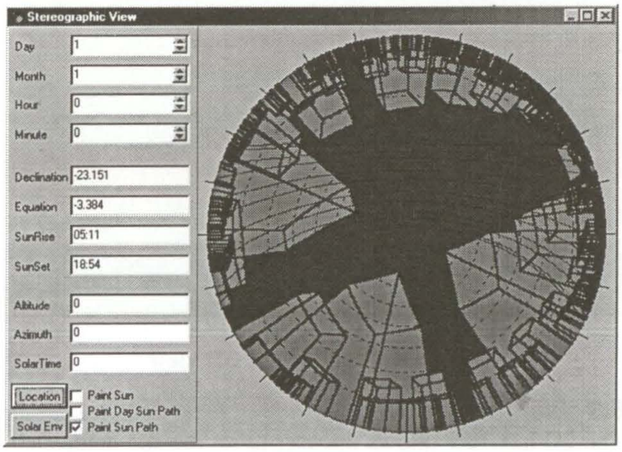
A sun-path diagram was needed to plot the pondered radiation values into. Given a latitude and longitude, the sun's altitude and azimuth are estimated for each month of the year, and then displayed using the stereographic method [Szokolay80] (Figure 6).



Day 1
Month 1
Hour 0
Minute 0
Declination -23.151
Equation -3.384
SunRise 05:11
SunSet 18:54
Altitude 0
Azimuth 0
SolarTime 0
☐ Paint Sun
☐ Paint Day Sun Path
☑ Paint Sun Path

Figure 6: BlockMagic generated 27.5°S Sunpath Diagram (North orientation)

The same method was used to plot the urban environment onto the sun-path diagram, resulting in the sky vault obstruction view (Figure 7).



Day 1
Month 1
Hour 0
Minute 0
Declination -23.151
Equation -3.384
SunRise 05:11
SunSet 18:54
Altitude 0
Azimuth 0
SolarTime 0
☐ Paint Sun
☐ Paint Day Sun Path
☑ Paint Sun Path

Figure 7: BlockMagic generated sky vault obstruction view

The sky vault view allows the solar envelope results to be seen in an easy to understand graphical way. If buildings are outside the limits of the solar envelope, smaller portions of the sky are visible, meaning the sun will not be visible for much time a day on those regions.

5.2 3D Visualization Techniques

BlockMagic's existing 3D navigational interface was upgraded, allowing the generation of realistic shadows in real time. This was implemented using the OpenGL library's stencil buffer, based on Porter and Cosmin's approach [Porter00].

1. The first step is to draw all faces of the scene as usual.
2. Then, we find which faces are neighbors to each other and which of them are facing the light.
3. The shadows are then rendered, first incrementing the stencil buffer with the front faces (casting the shadow). The shadow polygons are drawn as follows: for each face, if it is visible, check all of its edges; if at that edge there's no neighboring face, or the neighboring face is not visible, then that edge casts a shadow. A shadow polygon is defined by the edge casting the shadow into the infinity, i.e., it contains four vertices: v1 and v2 are the vertices from the current edge, v3 and v4 are calculated as a projection into the infinity of the light source over v1 and v2. The infinity is set as a very large number so that the shadow polygon will be clipped against all the polygons it encounters.
4. The shadows are rendered a second time, now decrementing the stencil buffer with the back faces ("turning off" the shadow between the object and any other surfaces). The shadow polygons are drawn as described in step 3.

A resulting scene is shown in Figure 8.

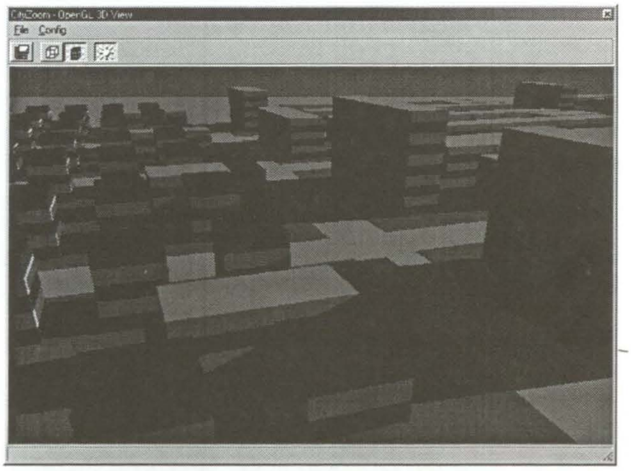
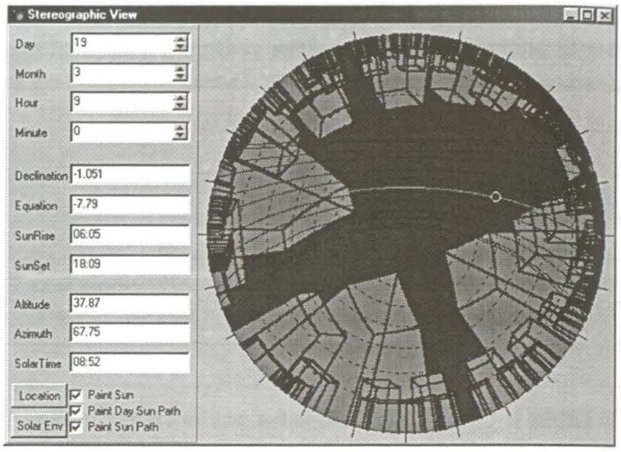


Figure 8: BlockMagic 3D view

5.3 User Interface

The 2D interface allows the user to set the site data, such as latitude, longitude, and climatic variables. It is also possible to set the month, day, hour, and minute, and view the sun position in the sky for those parameters (Figure 9).



Day 19
Month 3
Hour 9
Minute 0
Declination -1.051
Equation -7.79
SunRise 06:05
SunSet 18:09
Altitude 37.87
Azimuth 67.75
SolarTime 08:52
Location ☑ Paint Sun
☑ Paint Day Sun Path
Solar Env ☑ Paint Sun Path

Figure 9: Sun path for 03/19 and position at 9 AM

Changing the date and time in the 2D interface will also affect the 3D view, moving the sun (light source) position and generating the corresponding shadows. Figure 8 was generated for the configuration shown in Figure 9, resulting in a scenario with shadows cast for 3/19 at 9 AM. The user can use the mouse to translate and rotate the camera around the scenario without any movement restrictions.

6. FINAL COMMENTS

The integration of sunlight access parameters to a building potential simulator, and the implementation of 2D and 3D visualization methods were presented. Insolation can be simulated along with Master Plan's rules, through the use of the solar envelope technique, seeking to maximize both building potential and access to solar radiation. 2D visualization techniques are used to show the sun path in the sky as well as the sky vault obstruction. Based on simulation results and solar data, realistic shadows can be generated in real time in a 3D scenario, where the user can navigate.

Future work includes improvement of 3D user interface, by implementing a more realistic walkthrough, and new techniques for visualizing radiation values in building facades. These radiation values could be estimated either at a specific time and date, or for a user-defined time interval. Possible visualization methods would be mapping values to facade colors in the 3D scenario, or to color maps using Mosaic. Both solutions would further improve decision support in the CityZoom environment.

7. ACKNOWLEDGMENTS

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