Computational Issues in Urban Design: Developing a Strategy for Solar Impact Assessment

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A comprehensive method for identifying the impacts on solar access of large scale architectural projects still continues to be an important and controversial area in city planning and urban design. Previous research studies such as the Sun Wind and Pedestrian Comfort, a study of Toronto's Central Area, demonstrated approaches possible when dealing with solar issues related to urban design. Existing techniques for solar inventory, analysis and evaluation, while effective, are often dependent on single event analysis (shadow casting) or manual procedures that are time consuming and exceedingly complex especially when needed for day-to-day use by planners or architects involved in complex urban projects. The Centre for Landscape Research has undertaken as part of its research to develop a computational approach that would help city urban designers evaluate and represent the issues of solar access in an urban setting. This paper will outline a series of computational methods developed to utilize an existing municipal digital data base and to describe complex issues of solar access in terms of urban form and context. A technique will be described that quantitatively assesses the total solar potential of a site as compared to changes in solar access due to different urban design proposals. Two-, three- and four-dimensional representation techniques are developed to facilitate understanding of the analysis to users such as city officials, the public, developers, etc.

Keywords: solar assessment, urban design, open space, modeling visualization.

1 Context Of The Research

To assess the impact of sun and wind on pedestrian comfort, the City of Toronto's Planning and Development Department undertook the Cityplan '91 Report No. 25 *Sun, Wind and Pedestrian Comfort, a Study of Toronto's Central Area* (Bosselman et al., 1991).

It became evident in the course of the study that solar access to public open space was considerably more complex to evaluate than streets. This was due to the fact that open spaces such as parks have more variability in their physical attributes, such as, size, location, boundary configurations, and intended use. As a result, they were not as easily subject to simple evaluations or generic standards. Also, traditional manual methods or

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computer programs to cast shadows were too limiting in both time (to generate images over long periods of time) and in analytic capability (to quantitatively describe and summarize this information). To this end, the Planning and Development Department, City of Toronto entered into a research project with The Centre for Landscape Research (CLR) to develop an evaluation and computational procedure for assessing solar access issues relative to open space in the city core.

The computerized portion of the project was developed using the CLR facilities at the School of Architecture and Landscape Architecture, University of Toronto. The main hardware used were Silicon Graphic's 4D/310 VGX and Indigo with additional mathematical verification on a Macintosh IIcx. The software utilized was the CLR's own 4-D visualization Software, PolyTRIM (Center for Landscape Research, 1987-1992). This software has been under development at the CLR for the last seven years and has been successfully applied to a growing number of research, planning, and design projects for universities, public agencies, and private consultants. The solar access tools are to be added as a design and evaluation support feature.

2 Approach

The approach used in the research can be divided into two phases. The first was the development of a computerized procedure to automate the calculation of solar data. The objective was to allow the user to define a variety of solar variables such as, latitude, longitude, park boundary configuration, month, date, and time periods. A fan based on these parameters would then be calculated in a realistic time-frame for this analysis to be used in day-to-day work (on the average, it was a three- to four-hour process to analyze a site over a year period). This allowed the visualization of the fans in 3D, including information on site locations and context, e.g., buildings, including heights. The procedure was further developed to provide a quantitative assessment of the solar potential of an open space. This assessment compares the existing solar potential, derived from the current context, to changes in those conditions due to surrounding built form conditions.

Phase two was the testing of these modeling techniques on a site area to determine the relative impacts of different built form scenarios adjacent to the open space. This case study helped determine the criteria for solar access that allows an evaluation of specific solar access to an open space and enables a comparison between solar access standards and the resultant impact of different built form scenarios. This developed an understanding of the zoning implications (existing and proposed) for solar access related to the open space. From this test, a preferred approach for the evaluation of open spaces was devised. Subsequently standards and an evaluation procedure were proposed for consideration by City staff.

3 Assessment Procedures

The procedure applied to this research by the CLR was based on our computer experience in four dimensional assessment of planning and urban design issues (Littlehales, 1992). In conjunction with City staff (City of Toronto, Planning and Development Department, Architecture and Urban Design Division), a preliminary approach was developed to apply to the test site. The techniques and computational approach were based on the City's requirement to establish a more iterative and comprehensive method for providing practical and verifiable solar access data.

The first step was to define a set of procedures starting from the combined experience gained from the assessment of solar access criteria developed as part of our involvement with the Cityplan '91 No. 25 study. This involved four critical steps:

- The transfer of 2D and 3D digital data from the City to our system.
- The application of sophisticated solar position equations to be used for the construction of the solar fans and sunlight assessments.
- The development of a computational approach for describing solar fans including their attribute information (time, month).
- The development of a computational approach for describing cumulative shadow impacts for a given time period (raster tools).

3.1 Data Transfer

A critical factor in the ability of this research to be used is the state of existing digital data for a study area. One of the sub-objectives of this research was to see if the utilization of primarily digital data was practical in a study of this nature. The digital data needed for this process falls into two categories: data used to define target sites, and data that forms the basis of analysis of existing context or proposals. Target sites can be clearly identified by two-dimensional footprints of buildings, edges of walks and streets, as well as open spaces combined with the ground elevations at the edge of the target area. Contextual information and/or proposals are required in three-dimensional form, with simple extrusions proving to be detailed enough for these computational evaluations. For this process, the 2D base data was provided to the Urban Design Division by The City of Toronto's Public Works and the Environment Department. The Architecture and Urban Design Division then created the 3D data on this base from a variety of sources. The 2D and 3D information was created on an Intergraph System. The primary data exchange file format was 2D and 3D DXF files. Two-dimensional information was specified to be saved as DXF lines, polylines, circles, and arcs. Three-dimensional forms were to be kept as simple polylines with elevation and thickness for extrusion. The City attempted to provide the location of all features. The 3D DXF data that the City developed was based on plans at 1:2000 (metric) and aerial reconnaissance. It included; existing, proposed and allowable buildings on the site and surrounding context area, existing and proposed roadways, all tied to the Universal Trans Mercator Grid. For this type of problem, we specified the following data dimensions:

1. A context area of at least four blocks in all directions surrounding the site. In areas where the block information is unequal in dimension, the largest block distance should be used.
2. The information should include the location and heights of all existing buildings and the allowable footprint and height of future buildings.
3. Existing and proposed roadways.
4. Spot elevations at all roadway intersections and in blocks, plus other spot information where available (required for construction of 3D terrain).
5. Location of all features should be tied to the Universal Trans Mercator Grid and a separate overlay of that grid should be on all plans. This will allow accuracy in location of the solar fans.

The transfer of this data to our system and software was relatively smooth, but required an additional amount of time and manipulation to bring it together in a usable form.

This was due to the fact that each individual three-dimensional building was constructed in its own User Coordinate System (UCS) and needed to be in a World Coordinate System (WCS) as a common base. This translation of user-coordinate information in a DXF file format did not prove to be a simple process and caused much of the delay in the translation process. Furthermore, the simple extrusions created on the Intergraph system did not translate as polylines with thickness but rather as meshes, a fact that could not be corrected, and subsequently, a more advanced translator that supported meshing was required. These problems were due to the fact that this database had been constructed primarily for internal use and not specifically for this exercise.

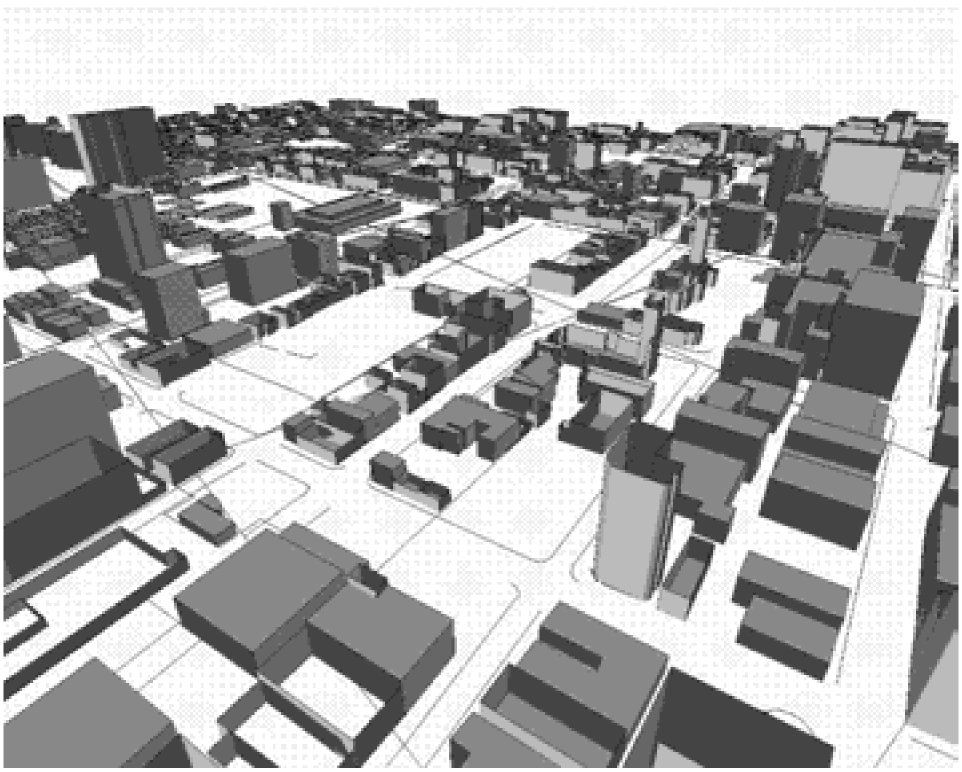

Figure 1. A Representation of Existing 3D Digital Data.

3.2 Solar Position Equations

To develop a quantitative foundation for the calculation of solar positions (local time, altitude and azimuth), we solicited the assistance of P. F. Ortiz, Ph.D. at the Astronomy Department, University of Toronto, who provided us with professionally-accepted formulas to determine solar position based on universal time, latitude, and longitude. These formulas were derived from the United States Naval Observatory's (USNO) *Program for Celestial Positions* (USNO, 1984). The calculations are considered in principle accurate but do not incorporate some minor effects on the motion of the Earth in space, although standard adjustments for solar refraction over the horizon were accounted for.

A program was developed in the C programming language and verified on two hardware platforms and two software development environments to ensure consistency of results. These results were also compared with the USNO program and found to be consistent (see Accuracy Assumptions). With this program information, time (universal and local), azimuth and altitude can be generated for any latitude, longitude, and time increment (month, day, time of day) desired. These equations are based on universal time and a translation between the local time zone as well as daylight savings time had to be accounted for in our code.

3.3 Solar Fan Generation

The solar fan generator allows one to develop a three-dimensional plane or fan that represents the lowest traveled path of the sun over a user-specified period of time (month, days, and time of day). This sets a three-dimensional plane, under which any development would not impact solar access to a target site. The procedure used to generate a solar fan is outlined below:

1. Define a target site area (an open-space boundary, or street edge). This site boundary can include elevation data to account for a sloped site or varying street conditions.
2. Define a fan boundary. This is the extent in which the solar fan will be constructed.
3. Establish the time period to be utilized in generating the fan. This includes the range of months, days within those months, time period within each day and number of intervals per hour to be evaluated.
4. The site area to be sampled must be divided into a grid. The grid size must be specified and will determine the spatial sampling used in generating the solar fan. The upper limit on the height of the fan is also specified at this time.
5. After selecting the boundary, target site, grid size and time period, the solar fan will be generated. For each time interval selected, the position of the sun is calculated applying the astronomical equations. The sun is then assumed to pass through each grid cell in the boundary area. If, after passing through the cell, it continues onwards and would fall upon the site area, that cell is tested to determine whether this is the lowest sun angle passing through this cell and hitting the park. If it is the lowest, then the grid is set to this ray's height. Once all time intervals have been evaluated, the area in the boundary is checked and any cells that did not get hit by the sun on the way to hitting the site or are above the specified height limit are discarded. The remaining cells are combined to form a plane or fan in three-dimensions.

By creating an image of the fan in three-dimensions, anyone can quickly visualize the path of the sun over the specified time period. When this fan is combined with the 3D model of the existing or proposed context, the interaction of the sun's movement and built-form can be visualized. Any built-form that extends through the solar fan will have an impact upon the site.

With the ability to see the cumulative lowest path of the sun, people were quickly able to visualize the built form that would cause shadows, its relative amount of solar interference and the implications of the variations which result from the time sample selection. The most evident anomaly was the waves at the edge of the fans due to the sampling of only one day in each month. Further sampling (every day for example) would smooth out the waves but substantially increase the computational load (it puts the computer out of the three- to four-hour visualization time). Along with the three-dimensional information for each cell, the time period that influenced its ultimate height is also recorded as a set of attributes to allow understanding of the critical influencing months, days, and times of day. This can quickly identify which periods of time an existing context or proposal will impact the site. By understanding this phenomenon, City staff were able to better understand the forms, computational criteria and the implications of time standards used in generating the solar fans.

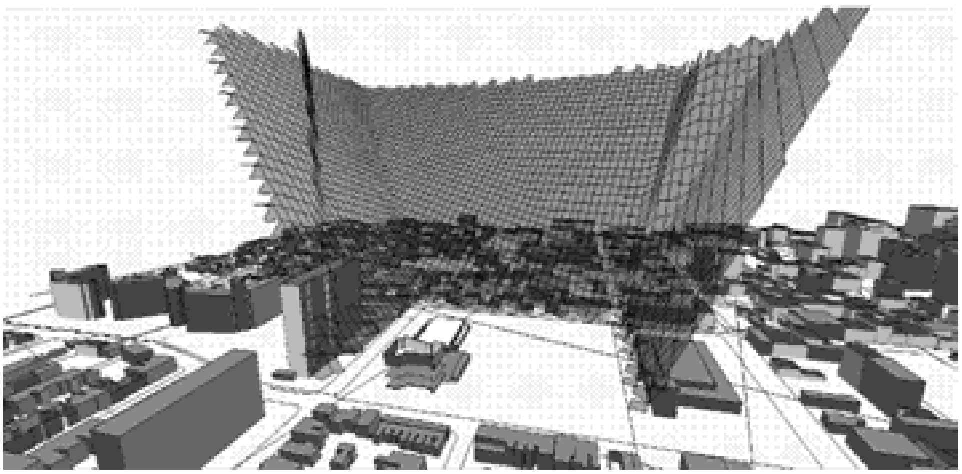

Figure 2. Solar Position Fan.

Furthermore, to aid in the understanding and the use of the three-dimensional fan in the planning and design process, a tool was also developed which allowed any fan generated by this technique to be transformed into a set of contours with the appropriate height and interval. This set of contours could then be visualized and plotted in more common two-dimensional views that are directly scaleable. This was considered important in relating the solar data into more conventional forms of representations such as zoning maps.

3.4 Solar Raster Tool

The solar raster tool was designed to evaluate a policy generated from a solar fan or density option. It does this by producing a cumulative record of the amount of direct sunlight that falls on a selected grid over the site. Its primary output is that of a raster map showing the total direct sunlight available over the time sample that falls upon each cell within the site. The process to perform this analysis is as follows:

1. Establish the site boundary over which the shadows will be tested.
2. Construct any three-dimensional models of existing context and/or proposed street edge zoning (46m street edge) so that shadows can be generated for them.
3. Set the solar time sample to be utilized in generating the shadows. This includes the range of months, days within those months, time period within each day and number of intervals per hour to be evaluated.
4. The detail to which the raster map will be generated must be specified as a grid size over the site.

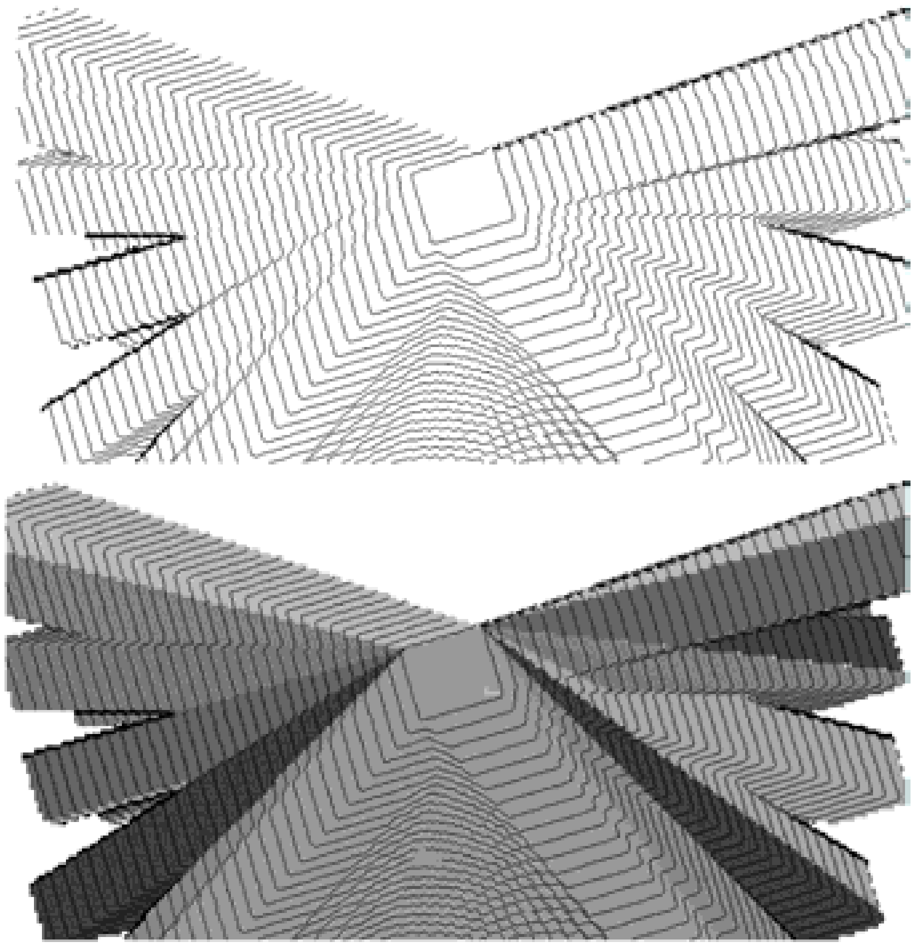

Figure 3. Representations of solar fan as a contour map (top) and as a contour map related to influencing months (bottom). This figure illustrates the wave effect due to sampling period.

5. After the target site and built forms are selected shadows are cast over the site for each time interval. For each interval, the sun angles are calculated and the shadows generated by the built form are projected. Those that fall upon the site are recorded. If two or more shadows cast at a particular time interval fall upon the same grid cell on the site, it is only registered as one shadow event (e.g., two buildings shading same area of the site for five minutes is the same as one). Once all time intervals are evaluated, the total number of times a grid cell was in shadow is divided by the total number of time intervals tested to produce a map of percentage sunlight falling upon the park.

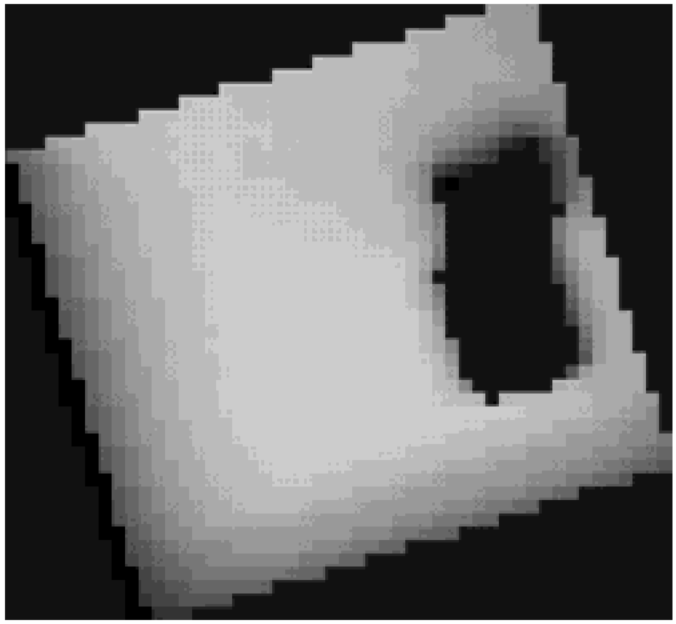

Figure 4. Raster Map Showing Solar Accumulation Across Individual Cells.

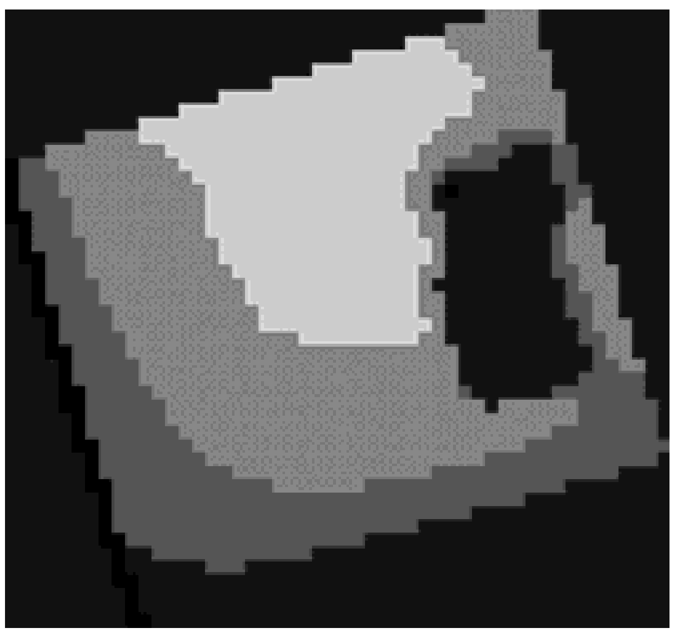

Figure 5. Solar Raster Map Showing Summary of Shadow Categories Across the Site

At the end of this analysis there was a need to summarize the information contained in the raster map to allow simple quantitative comparisons between alternatives on the same site. To do this, a tool was developed that calculated the sum of the solar access on each cell and divided that total by the number of cells. This gives a single number that is easy to compare alternatives against. It does not, however, differentiate between whether all the site is receiving an equal amount of sun/shade or only a portion of the site is in sun or shade all the time. For example a complete site receiving only 50% sunlight would be equivalent to a site in which half was in full sunlight and the other half in total shade. It was important to use this information in conjunction with the raster maps to allow for a more critically informed interpretation.

4 Study Assumptions And Accuracy

During the course of this research, the factors affecting the accuracy of the resultant fans and raster maps were examined. Accuracy issues fell into four categories, those based upon the 2D and 3D digital data, those in the solar equations, those which are the result of time period sampling and other factors related to modelling of complex solar environments.

An assumption was made that the accuracy of the 2D and 3D information received was established by the City and therefore deemed to be accurate for purposes of this study. Independent verification of the accuracy of horizontal data (X and Y values) and height (Z, values) was therefore not conducted.

This can be a critical issue as an accuracy criterion of +/- 10 cm is considered desirable for horizontal and vertical input in order to produce solar access predictions with an accuracy of +/- 1.5m (Bosselman, 1991:122). This accuracy usually far exceeds standard digital data bases unless verified or modified to meet this criterion. For purposes of this study the level of information is deemed to be adequate for planning level investigations.

All sites and their contexts were assumed to be flat. In the majority of cases the sites evaluated had relatively little variation in topography related to planning scale investigations. These generally fell in the range of 1-2% slope. Specific tools have been developed to allow more topographical sensitive analysis but were only applied to a site that had a 3-4 meter drop across its boundary.

For this study latitude was set at 43.39˚ N; longitude at 79.23˚ W. All times were based on Local Eastern Standard Time including shifts related to Daylight Savings. This is consistent with the information used in Cityplan '91 Report No. 25. The base solar equations deal with the following accuracy limitations:

> Angular quantities are subject to errors which at most amount to 0.3˚. Time quantities would be accurate to within the minute, but note that sunrise and sunset times are affected by atmospheric refraction and though some of it is taken into account by the equations, atmospheric conditions change without regular pattern and can be larger than average conditions used in the equations.[1]

[1]. Personal correspondence to R. Wright, CLR by P. F. Ortiz Ph.D., Graduate Astronomy Student Association, Department of Astronomy, University of Toronto, January 31, 1992.

The time sample used was every 15 minutes of the day for the 21st of each month from March to and including September (from the spring to the fall equinox). The calculations are accurate to six minutes of time from sunrise and sunset.

Since no sophisticated error checking was done relative to the 2D and 3D data received, it is difficult to set a margin of error. The error will be dependent not only on the geometric data but is also dependent on the grid cell size utilized for the raster mapping of solar potential. With good 3D data and a fine grid cell sampling, the error factor could be as little as a 1-2%. However, for purposes of this study we would estimate a 4-6% error factor.

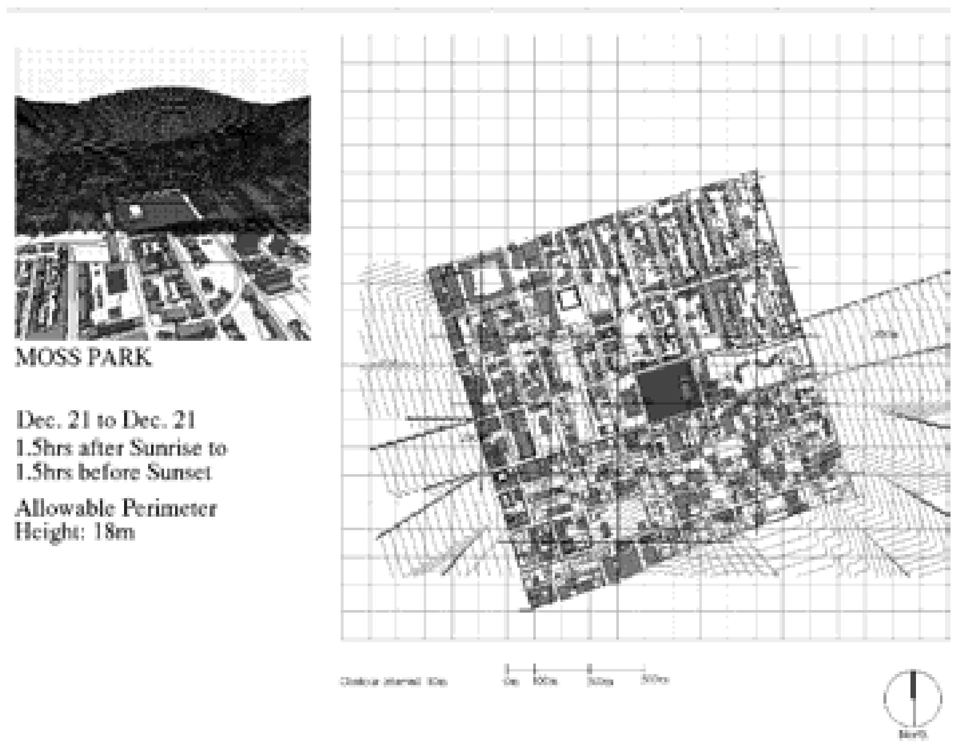

Figure 6. Solar Fan And Contour Map For A Typical Study Site.

Some of the implications for time period sampling have been discussed in the section above on solar fan generation. There are two clear issues in selecting time sample periods for solar models. The first is based upon the number of sample time periods selected, i.e., months, days, and minutes. In any time period selected it is important to identify what types of solar events are critical to consider and what level of accuracy is required to support the decisions being made. In this study, we selected a fine sampling period within each day (every 15 minutes) to capture the influence of sunrise and sunset and a coarse sampling period for each month (only one day). This resulted in sharp breaks between each month's influence as is evident within each fan (see Figure 3). This is representative of traditional methods that use the 21st of each month (days that include the extremes of equinoxes and solstice periods) and is consistent with the approach used in Cityplan '91

Report No. 25. This sampling period allowed us to ensure a two- to three-hour turnaround period for solar access evaluations. A finer number of samples, e.g., more days, would result in a smoother and more accurate transition between months. This would result in a somewhat lower solar plane and more restrictive planning envelope. In the sites tested, the sampling criteria proved to be adequate for evaluating existing zoning against proposed built form scenarios. In other words, it clearly showed what buildings significantly penetrated the fan and what zoning was more restrictive at present than the plane itself. More tests will need to be conducted to determine the impact on policy of increased accuracy in sites where the zoned heights are close to the same heights determined by the solar fan.

Finally, this study was focused at determining the impacts of urban design scenarios only on direct sunlight. In addition, it assumed that the amount of sunlight available during the time periods tested was optimum. Since the intent is to optimize any potential for sunlight and to minimize any potential for shading by surrounding buildings, provision for sunlight even in the winter months was considered desirable. No probability model of the actual potential for sunlight due to climatic factors (e.g., cloud cover) was incorporated either in the code or in the evaluation procedures.

In any case, the point is not to provide a tool with unlimited accuracy or complexity but to find a strategy for evaluating existing policy and determining the impact of new policy proposals on built form. The computational approach developed here allows for a balancing between the accuracy and complexity required and a realistic amount of time necessary to make a decision.

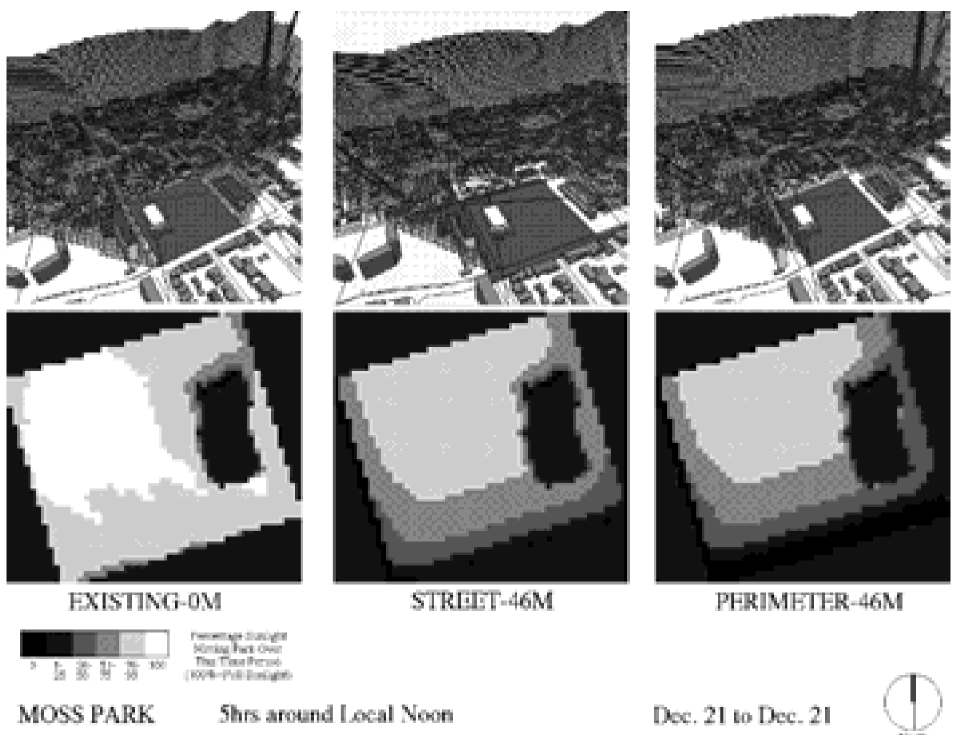

Figure 7. Solar Fans And Associated Solar Raster Maps For A Typical Study Site.

5 Conclusions

The experience gained from Cityplan '91 Report No. 25 indicated that the complexity of analyzing open space must be structured in a way that allows for a more thorough exploration of the balance between optimum direct solar access and appropriate urban context. Open spaces because of their characteristics do not yield easily to simplistic generic solar standards, simple shadow casting or manual procedures. An optimum process would allow for the development of experience through evaluating the impacts of a number of options for solar access in specific situations. It must allow the planner or urban designer to comparatively evaluate those results against a larger number of other urban spaces in similar and varying contexts. Individual planners and architects at the city level need to be able to iteratively explore the planning or design implications and to determine practical approaches for optimizing solar access.

To date this type of exploration has been limited by the complexity of accessing data, the clumsiness of existing computer shadow casting or manual procedures, the need to communicate the implications of solar impacts to a wide range of users and the need to provide an analytic framework that is defensible. This research has attempted to develop such a computational approach and has provided us with insights of the issues surrounding wide-scale application of computational methods to problems of this sort.

5.1 Digital Data

A computational procedure for predicting impact on solar access in urban areas is dependent on a comprehensive 3D data base. Many city organizations have developed digital databases, but these are usually oriented to some previous intended use and not structured for external use. The 3D data base constructed by the City of Toronto was developed for visual representation of architectural form (primarily at ground level) and was more detailed than required for solar analysis. Although more detailed at ground level, no base elevations of buildings on terrain nor verified height information were available. These factors strongly influenced the accuracy of the analysis, impeded turn-around time and complicated data translation. Access first, to data and then to data structured efficiently and accurately for a variety of analytical tasks continues to be an obstacle to the application of computer methods. These difficulties will hamper the use of this technique until a protocol for urban information is developed.

5.2 Visualization

Visualization of the process and results of analysis were key parts of the research. The development of 3D models, solar fans and analytic raster maps helped City staff understand the implications of urban form on solar access to open space. It also made the method more visible and explicit to the user (from experts to lay people) so that results and what are more important assumptions are clearly portrayed allowing them to participate and evaluate the process. It was also apparent during the research that a variety of abstractions of the same data (plans, perspective views, attribute information) were necessary to allow for full comprehension of the study results.

5.3 Analysis

Most traditional computer software in use by city governments related to solar analysis are based on shadow casting programs. The City of Toronto had difficulty utilizing such approaches due to the general lack of analytic capability of these programs and the time required to generate multiple shadow passes in complex urban contexts. This research has shown that quantitative analysis of the dynamics of solar access in urban areas requires a more rigorous approach. Results must be capable of showing the cumulative impacts of a complete time period and must be able to be translated into comparable indices for practical decision making. Users must be able to change criteria and examine the quantitative and visual implications of those modifications and assumptions.

5.4 Administrative Application

It is important for a computational approach to solar analysis to be able to translate the results and conclusions of the research into terms that can be integrated into normative planning procedures. This research has shown that something as simple as the solar contour generator was considered key by users for presenting the implications of certain policy decisions and for purposes of comparison to existing zoning strategies. The 3D representation of the data and options explored was important in gaining acceptance by key managers responsible for administration and application of the research at the City. The development of high-end computing approaches in planning and architecture is often difficult to implement in the traditional planning and design process. The utility of the methods developed here will depend on either the demand for cities to provide more defensible procedures due to legal requirements or the desire to proactively develop or evaluate policy that protects solar access prior to conflict.

5.5 Implications of the Research

This research demonstrates that the technology and tools are becoming readily available and applicable to questions of complex analysis in urban design such as solar access evaluation. It was evident in the process of developing these tools that data organization and handling protocols are essential for the use of existing data in a variety of analytical techniques. While the ability to utilize these tools in an iterative and realistic time frame have been realized, the issue of more complex technological integration still remains as an obstacle to administrative acceptance.

We believe that urban design issues are a rich area for developing applied research. The ability of urban design or planning departments to understand and take advantage of such research will not emerge until there is a better understanding and demonstration of the possible application of computational techniques in day-to-day work.

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